# UNIT-1

# PRINCIPLES OF QUANTUM MECHANICS

## FAILURES OF CLASSICAL MECHANICS:-

It doesn't explain

- The stability of atoms
- Origin of discrete spectra of atoms
- Spectrum of black body radiations
- Photo electric effect, Compton Effect, Zeeman Effect, Raman Effect.

**Newton corpuscular theory:**

Light consists of minute fast moving elastic particles known as corpuscles.

But it fails to explain interference, diffraction, and polarisation.

**Huygens wave theory and Maxwell's electromagnetic theory:**

Light travels in the form of waves in hypothetical medium ether.

Successfully explained the phenomenon of interference, diffraction polarisation.

**Quantum theory of light by max Planck:**

Matter is composed of a large no. of oscillating particles which vibrate with different frequencies.

Energy of oscillating particle is quantised.

$E= nh\vartheta$

When they move from one state to another state It emits or absorbs energy.

$$\Delta E = h\vartheta$$

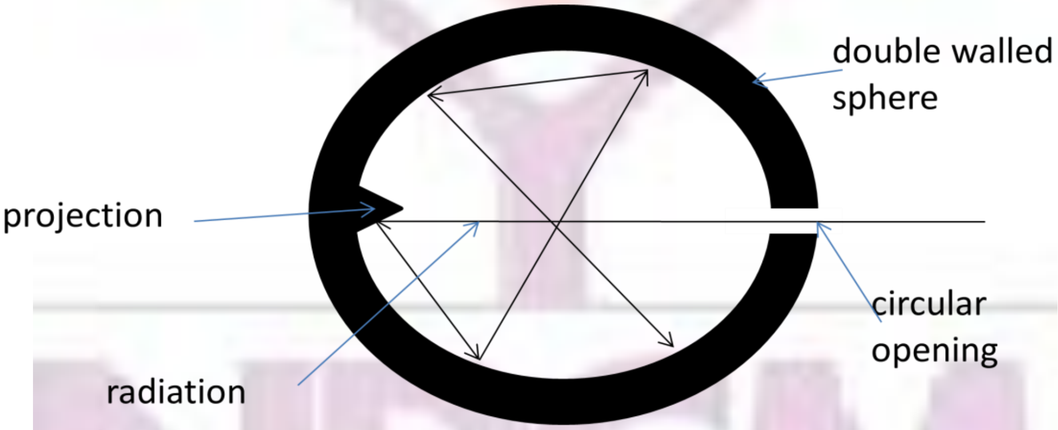
This emission and absorption of energy is not continuous but it takes place in discrete amounts of $h\vartheta$.

Exchange of energy between light and matter is not continuous, but it is small bundles or packets or quanta of definite energy proportional to frequency of light. These small packets of energy are called photons, which propagate with light speed.

## BLACK BODY RADIATIONS:

A black body is a body which absorbs the radiations of all wavelengths incident up on it. It neither reflects nor transmits any of the incident radiations and therefore appears black whatever be the colour of radiation. When a black body is heated, it emits radiations which are known as black body radiations. No actual body is a perfect black body. A black body can artificially constructed

**Construction**: According to Ferry, a black body consists of a hollow thick double walled sphere, painted lamp black internally and provided a small circular opening to enter the radiations. A projection is placed in front of the opening to prevent the direct reflection. When a radiation enters, it suffers many reflections inside the sphere and is finally absorbed.



**Stefan's law:**

According to Stefan, when a black body is heated to some temperature T, the total energy emitted by it is directly proportional to fourth power of the temperature.

$$E \propto T^4$$

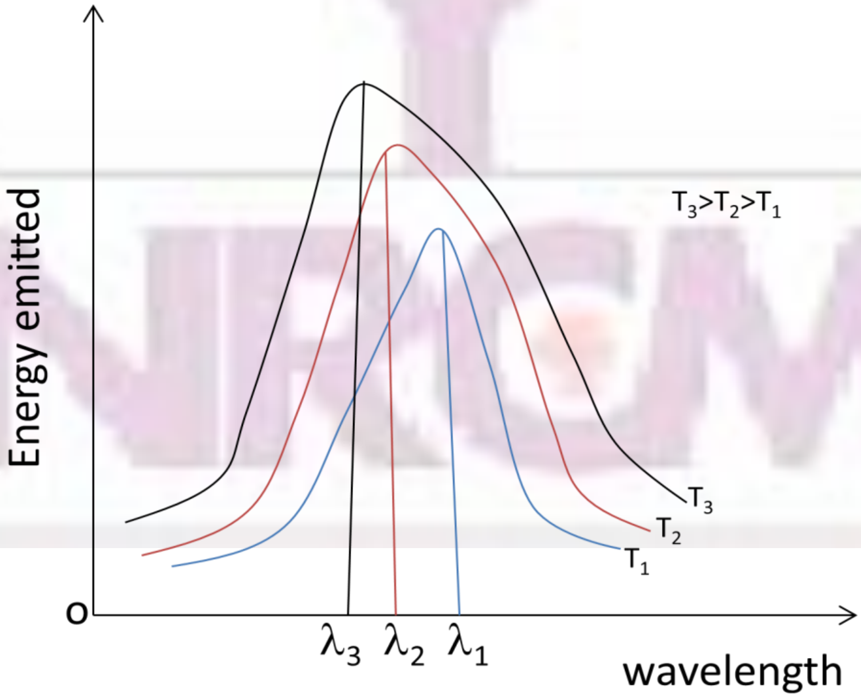
$$E = \sigma T^4$$

Where σ is called stefan's constant.

**Energy Distribution Curves:**

- The distribution of energy in a black body for different wavelengths at different temperatures was experimentally determined by Lumer and Pringshen in 1899. so, according to them,
- The emission from a black body at any temperature is composed of radiation of all wavelengths
- The total energy of radiation at any temperature is given by the area under the curve.
- As the temperature of the black body increases, the intensity of energy of the radiation for each wave length increases.
- The wave length corresponding to the maximum energy shift towards shorter wavelength as the temperature increases. This is called Weins-Displacement Law.

$\lambda_m$ X T=constant



## PLANCK'S LAW:

**Statement:**

According to this law, the energy emitted by a black body with in a wavelength range λ to λ+dλ is given by

$$E_\lambda d\lambda = \left| \frac{8\pi hc}{\lambda^5} \times \frac{1}{\left[exp\left[\frac{hc}{\lambda KT}\right] - 1\right]^1} d\lambda \right|$$

**Proof:** According to Planck's hypothesis,

A black body consists of number of oscillators inside the cavity of the black body.

Each oscillator can have discrete set of energies given by,

$$E_n = nh\nu \qquad n = 0,1,2,3, \dots\dots\dots$$

If N is the number of oscillators inside the cavity and E is the total energy. Then, the average energy per oscillator is

$$\bar{E} = \frac{E}{N}$$

Let $N_o$, $N_1$ , $N_2$, $N_3$, $N_4$, ....... be the oscillators inside the cavity with energy 0, hυ, 2hυ, 3hυ, 4hυ,....... respectively.

Therefore,

$N= N_o+ N_1+N_2+N_3+ N_4+$ .......

$E= (0)N_o+(h\upsilon)N_1+(2h\upsilon)N_2+(3h\upsilon)N_3+ (4h\upsilon)N_4+$ .......

$E= (h\upsilon)N_1+(2h\upsilon)N_2+(3h\upsilon)N_3+ (4h\upsilon)N_4+$ .......

According to Maxwell-Boltzmann distribution law, the number of oscillators having (rhυ) energy is given by,

$$N_r = N_0 \, exp\left[\frac{-rh\nu}{KT}\right]$$

The total number of oscillators,

N= $N_o$+ $N_1$+$N_2$+$N_3$+ $N_4$+ .......

$$N = N_0\, exp\left[\frac{-0h\nu}{KT}\right] + N_0\, exp\left[\frac{-1h\nu}{KT}\right] + N_0\, exp\left[\frac{-2h\nu}{KT}\right] + N_0\, exp\left[\frac{-3h\nu}{KT}\right] + \dots\dots\dots$$

$$N = N_0 + N_0\, exp\left[\frac{-h\nu}{KT}\right] + N_0\, exp\left[\frac{-2h\nu}{KT}\right] + N_0\, exp\left[\frac{-3h\nu}{KT}\right] + \dots\dots\dots$$

$$N = N_0\left[1 + exp\left[\frac{-h\nu}{KT}\right] + exp\left[\frac{-2h\nu}{KT}\right] + exp\left[\frac{-3h\nu}{KT}\right] + \dots\dots\dots\right]$$

$$N = N_0\left[1 + exp\left[\frac{-h\nu}{KT}\right] + \left[exp\left[\frac{-h\nu}{KT}\right]\right]^2 + \left[exp\left[\frac{-h\nu}{KT}\right]\right]^3 + \dots\dots\dots\right]$$

$$let\ x = exp\left[\frac{-h\nu}{KT}\right]$$

$$N = N_0\,[1 + x + [x]^2 + [x]^3 + \dots\dots\dots]$$

$$N = N_0\,[1 - x]^{-1}$$

$$N = \frac{N_0}{[1-x]} = \frac{N_0}{\left[1 - exp\left[\frac{-h\nu}{KT}\right]\right]}$$

The total energy is given by

E= (hυ)$N_1$+(2hυ)$N_2$+(3hυ)$N_3$+ (4hυ)$N_4$+ .......

$$E = \left\{(h\nu)N_0\, exp\left[\frac{-1h\nu}{KT}\right]\right\} + \left\{(2h\nu)N_0\, exp\left[\frac{-2h\nu}{KT}\right]\right\} + \left\{(3h\nu)N_0\, exp\left[\frac{-3h\nu}{KT}\right]\right\} + \cdots\dots\dots\dots$$

$$E = \left\{(h\nu)N_0\, exp\left[\frac{-1h\nu}{KT}\right]\right\} \times \left[1 + \left\{(2)\, exp\left[\frac{-h\nu}{KT}\right]\right\} + \left\{(3)\, exp\left[\frac{-2h\nu}{KT}\right]\right\} + \cdots\dots\dots\dots\right]$$

$$let\ x = exp\left[\frac{-h\nu}{KT}\right]$$

$$E = \{(h\nu)N_0\, x\} \times [1 + \{(2)\, x\} + \{(3)\, x^2\} + \{(4)\, x^3\} + \cdots\dots\dots\dots]$$

$$E = \{(h\nu)N_0\, x\} \times [1 - x]^{-2}$$

$$E = \frac{\{(h\nu)N_0\, x\}}{[1-x]^2}$$

$$E = \frac{\left\{(h\nu)N_0\, exp\left[\frac{-h\nu}{KT}\right]\right\}}{\left[1 - exp\left[\frac{-h\nu}{KT}\right]\right]^2}$$

Average energy of the oscillator,

$$\bar{E} = \frac{E}{N}$$

$$\bar{E} = \frac{\dfrac{\left\{(h\nu)N_0 \, exp\left[\frac{-h\nu}{KT}\right]\right\}}{\left[1 - exp\left[\frac{-h\nu}{KT}\right]\right]^2}}{\dfrac{N_0}{\left[1 - exp\left[\frac{-h\nu}{KT}\right]\right]}}$$

$$\bar{E} = \frac{\left\{(h\nu) \, exp\left[\frac{-h\nu}{KT}\right]\right\}}{\left[1 - exp\left[\frac{-h\nu}{KT}\right]\right]^1}$$

$$\bar{E} = \frac{(h\nu)}{\left[\dfrac{1 - exp\left[\frac{-h\nu}{KT}\right]}{exp\left[\frac{-h\nu}{KT}\right]}\right]^1}$$

$$\bar{E} = \frac{(h\nu)}{\left[\dfrac{1}{exp\left[\frac{-h\nu}{KT}\right]} - \dfrac{exp\left[\frac{-h\nu}{KT}\right]}{exp\left[\frac{-h\nu}{KT}\right]}\right]^1}$$

$$\bar{E} = \frac{(h\nu)}{\left[exp\left[\frac{h\nu}{KT}\right] - 1\right]^1}$$

The number of oscillators per unit volume in a frequency range υ to υ+dυ is,

$$N = \frac{8\pi\vartheta^2}{c^3} \, d\vartheta$$

Therefore the energy per unit volume with in the frequency range υ to υ+dυ is,

$$E_\vartheta d\vartheta = N\bar{E}$$

$$E_\vartheta d\vartheta = \frac{8\pi\vartheta^2}{c^3} \, d\vartheta \times \frac{(h\nu)}{\left[exp\left[\frac{h\nu}{KT}\right] - 1\right]^1}$$

$$E_\vartheta d\vartheta = \frac{8\pi h\vartheta^3}{c^3} \times \frac{1}{\left[exp\left[\frac{h\nu}{KT}\right] - 1\right]^1} \, d\vartheta$$

This is Planck’s law in terms of frequency

We know that

$$\vartheta = \frac{c}{\lambda} \;\&\; E_{\vartheta} d\vartheta = -E_{\lambda} d\lambda$$

On differentiation

$$d\vartheta = -\frac{c}{\lambda^2} d\lambda$$

On substitution,

$$E_{\lambda} d\lambda = -E_{\vartheta} d\vartheta = -\left[\frac{8\pi h\left(\frac{c}{\lambda}\right)^3}{c^3} \times \frac{1}{\left[exp\left[\frac{hc}{\lambda KT}\right]-1\right]^1}\left(-\frac{c}{\lambda^2} d\lambda\right)\right]$$

$$E_{\lambda} d\lambda = \left[\frac{8\pi hc}{\lambda^5} \times \frac{1}{\left[exp\left[\frac{hc}{\lambda KT}\right]-1\right]^1} d\lambda\right]$$

This is Planck’s law in terms of wavelength

**Wien's formula:**

This formula is applicable on shorter wavelength side of the Planck's law

$$E_{\lambda} d\lambda = \left[\frac{8\pi hc}{\lambda^5} \times \frac{1}{\left[exp\left[\frac{hc}{\lambda KT}\right]-1\right]^1} d\lambda\right]$$

So, when $\lambda$ is small, $1/\lambda$ is very large

Therefore

$$exp\left[\frac{hc}{\lambda KT}\right] \gg 1$$

Hence 1 can be neglected from the denominator of the Planck's law

$$E_{\lambda} d\lambda = \left[\frac{8\pi hc}{\lambda^5} \times \frac{1}{exp\left[\frac{hc}{\lambda KT}\right]} d\lambda\right]$$

This is called Wien's formula.

**Rayleigh jeans formula:**

This formula is applicable on longer wavelength side of the Planck's law

$$E_\lambda d\lambda = \left[\frac{8\pi hc}{\lambda^5} \times \frac{1}{\left[exp\left[\frac{hc}{\lambda KT}\right]-1\right]^1} d\lambda\right]$$

So, when λ is large, 1/ λ is very small

Then,

$$exp\left[\frac{hc}{\lambda KT}\right] = 1 + \frac{hc}{\lambda KT} + \left[\frac{hc}{\lambda KT}\right]^2 + \left[\frac{hc}{\lambda KT}\right]^3 + \ldots\ldots\ldots$$

$$since, \frac{hc}{\lambda KT}\ is\ small, higher\ order\ terms\ can\ be\ neglected\ in\ the\ above\ expression$$

Hence,

$$exp\left[\frac{hc}{\lambda KT}\right] = 1 + \frac{hc}{\lambda KT}$$

On substitution,

$$E_\lambda d\lambda = \frac{8\pi hc}{\lambda^5} \times \frac{1}{\left[1+\frac{hc}{\lambda KT}-1\right]^1} d\lambda$$

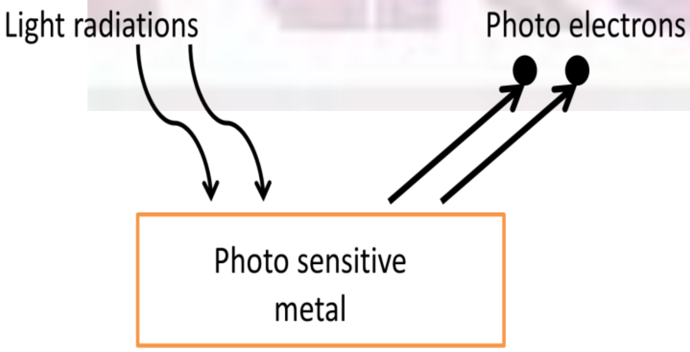
$$E_\lambda d\lambda = \frac{8\pi hc}{\lambda^5} \times \frac{1}{\left[\frac{hc}{\lambda KT}\right]^1} d\lambda$$

$$E_\lambda d\lambda = \frac{8\pi KT}{\lambda^4}\ d\lambda$$

This is called Rayleigh jeans formula

## PHOTO ELECTRIC EFFECT:

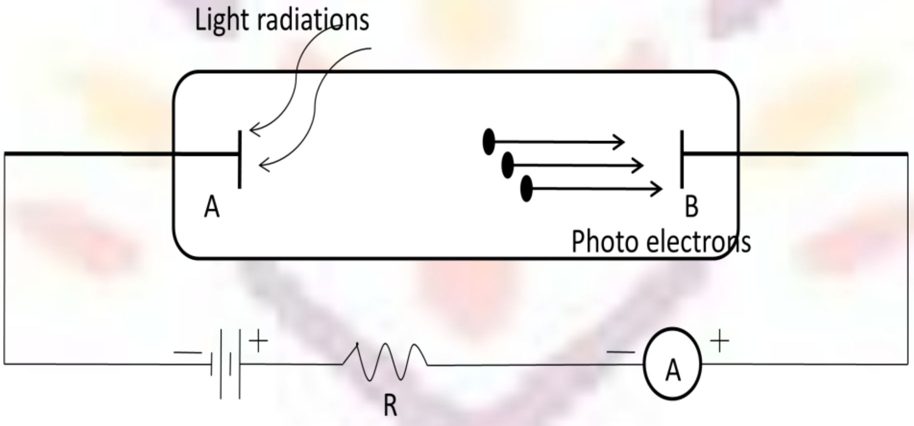
When a light of suitable frequency illuminates a metal surface, electrons are emitted from the metal surface. These photo generated electrons are called photo electrons.



**Experimental Verification:**

Arrangement consists of

- Two photo sensitive plates A and B enclosed in a quartz bulb. Plate A is connected to negative terminal of battery and plate B is connected to positive terminal of battery through a ammeter and a resistor. Hence, plate A acts like a cathode and plate B acts like a anode.
- When light radiations are made to fall on plate A, the photo electrons are emitted by it and are attracted by the anode (plate B). Hence there is a flow of current in the circuit called as photo electric current.



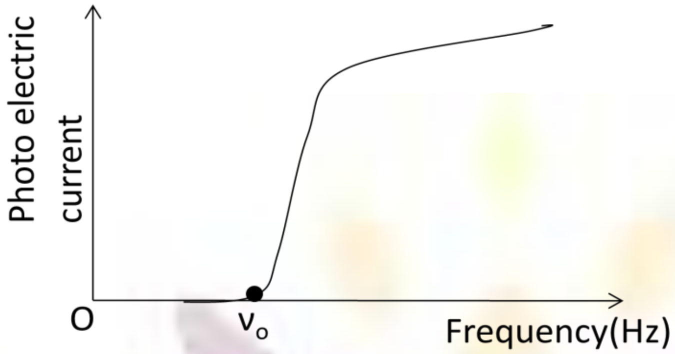
- This photo electric current is a function of
  - Incident light radiation frequency
  - Intensity of incident light radiation
  - Voltage potential across the plates
- Plate A is the metallic surface in which electrons requires a minimum energy to escape out from the metal surface. This minimum energy is called as work function.

$\Phi = h\,\nu_o$

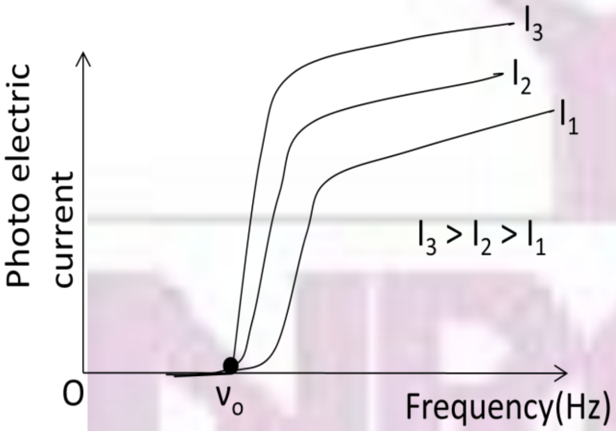
**Variation of Photo Electric Current**

<u>With frequency of incident radiation</u>: Keeping intensity of incident radiation and applied potential as constant, if the frequency of the incident radiation increases, then up to

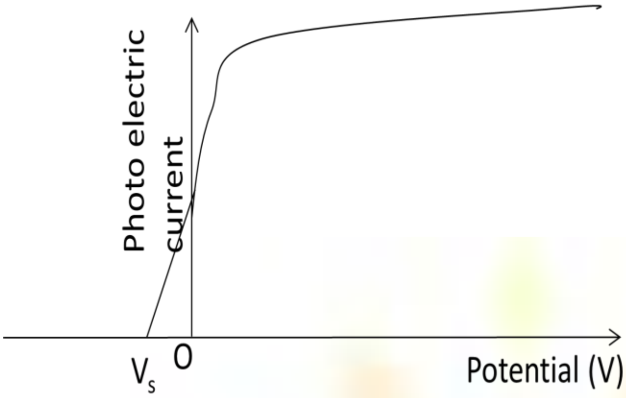
certain frequency called threshold frequency ($\nu_o$), the photo current is zero and after that varies as shown



With intensity of incident radiation: Keeping applied potential as constant, if the intensity of the incident radiation increases, then the photo current also increases. But the threshold frequency remains constant for a given material even the intensity increases



With applied potential: Keeping intensity and frequency of radiation as constant, if the applied potential increases, then the photo current also increases and becomes steady. Even if the applied potential is zero, there will be certain current in the circuit due to constant incident radiations. To make this current as zero if the reverse potential is increased, current decreases and becomes zero at a potential called as stopping potential



**Einstein Photo Electric Equation:**

According to Einstein, when light of energy (hν) is incident on a metal surface, a part of incident energy ($h\nu_o$) is utilized to remove electron from the material and remaining energy ($h\nu-h\nu_o$) is appeared as kinetic energy of the electron. There fore

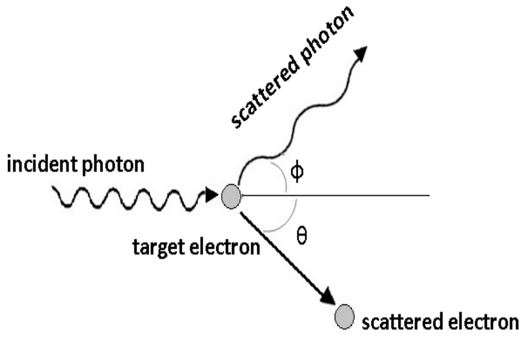
$(h\nu-h\nu_o)$=K.E

$(h\nu-h\nu_o)=1/2\ m\ v^2$

The above equation is called as Einstein photo electric equation. Where $\varphi=h\nu_o$ is called as work function.

## COMPTON EFFECT:

Statement: When a mono chromatic beam of high frequency radiation is scattered by a substance, the scattered radiation contains two components. One having wavelength greater than the incident called as modified component and other having the same frequency as the incident called as unmodified radiation.



**Derivation:**

let us consider a x-ray photon collide with an electron at rest.

Energy of incident photon= $h\upsilon$

Momentum of incident photon= $h\upsilon/c$

Let $m_o$ be the rest mass of electron.

Energy of rest electron= $m_oc^2$

Momentum of rest electron= 0

Before collision,

Energy of the system before collision= $h\upsilon + m_oc^2$

Momentum of the system before collision= $h\upsilon/c+0$

Let $\phi$ and $\theta$ be the scattering and recoil angle of photon and electron respectively.

Then,

energy of scattered photon= $h\upsilon'$

momentum of scattered photon= $h\upsilon'/c$

energy of recoil electron= $mc^2$

momentum of recoil electron= $mv$

After collision,

Energy of the system after collision= $h\upsilon' + mc^2$

Momentum of the system after collision= $h\upsilon'/c + mv$

Applying law of conservation of energy,

Energy before collision=energy after collision

$h\upsilon + m_oc^2 = h\upsilon' + mc^2$

$mc^2 = h\upsilon - h\upsilon' + m_oc^2$

$mc^2 = h(\upsilon - \upsilon') + m_oc^2$

Squaring on both sides

$(mc^2)^2 = (h(\upsilon - \upsilon') + m_oc^2)^2$

$$m^2c^4 = [h(\upsilon - \upsilon')]^2 + (m_oc^2)^2 + 2h(\upsilon - \upsilon')\, m_oc^2$$

$$m^2c^4 = h^2(\upsilon - \upsilon')^2 + m_o{}^2c^4 + 2h(\upsilon - \upsilon')\, m_oc^2$$

$$m^2c^4 = h^2\upsilon^2 + h^2\upsilon'^2 - 2h^2\upsilon\upsilon' + m_o{}^2c^4 + 2h(\upsilon - \upsilon')\, m_oc^2 --------(1)$$

Applying law of conservation of momentum

along the incident radiation,

$$\frac{h\nu}{c} = \frac{h\nu'}{c}\cos\phi + m v \cos\theta$$

$$\frac{h\nu}{c} - \frac{h\nu'}{c}\cos\phi = m v \cos\theta$$

$$m v c \cos\theta = h\nu - h\nu' \cos\phi$$

*squaring on both sides*

$$(m v c \cos\theta)^2 = (h\nu - h\nu' \cos\phi)^2$$

$$m^2 v^2 c^2 (\cos\theta)^2 = (h\nu)^2 + (h\nu' \cos\phi)^2 - 2\,(h\nu)(h\nu' \cos\phi)$$

$$m^2 v^2 c^2 (\cos\theta)^2 = h^2\nu^2 + h^2\nu'^2(\cos\phi)^2 - 2\,h^2\nu\nu' \cos\phi$$

Perpendicular to the incident radiation

$$\frac{h\nu'}{c}\sin\phi = -\,m v \sin\theta$$

$$0 = \frac{h\nu'}{c}\sin\phi + m v \sin\theta$$

$$h\nu' \sin\phi = -\,m v c \sin\theta$$

*squaring on both sides*

$$(m v c \sin\theta)^2 = (h\nu' \sin\phi)^2$$

$$m^2v^2c^2(\sin\theta)^2 = h^2v'^2(\sin\phi)^2$$

$adding\ above\ two\ final\ expressions$

$$m^2v^2c^2\,(\cos\theta)^2 + m^2v^2c^2(\sin\theta)^2 = h^2v^2 + h^2v'^2(\cos\phi)^2 - 2\,h^2vv'\cos\phi + h^2v'^2(\sin\phi)^2$$

$$m^2v^2c^2 \;=\; h^2v^2 + h^2v'^2 - 2\,h^2vv'\,\cos\phi \;---- (2)$$

Subtracting eq (2) from eq(1)

$$m^2c^4 - m^2v^2c^2$$
$$= h^2\upsilon^2 + h^2\upsilon'^2 - 2h^2\upsilon\upsilon' + m_o^2c^4 + 2h(\upsilon-\upsilon')\,m_oc^2 - h^2v^2 - h^2$$
$$+\,2\,h^2vv'\,\cos\phi$$

$$m^2c^2(c^2 - v^2) = -2h^2\upsilon\upsilon' + m_o^2c^4 + 2h(\upsilon-\upsilon')\,m_oc^2 + 2\,h^2vv'\,\cos\phi$$

$$m^2c^2(c^2 - v^2) = m_o^2c^4 + 2h(\upsilon-\upsilon')\,m_oc^2 - 2\,h^2vv'\,(1-\cos\phi)$$

From special theory of relativity

$$m = \frac{m_o}{\sqrt{1-\frac{v^2}{c^2}}}$$

$squaring\ on\ both\ sides$

$$m^2 = \frac{m_o^2}{1-\frac{v^2}{c^2}} = \frac{m_o^2c^2}{c^2-v^2}$$

$$m^2(c^2-v^2) = m_o^2c^2$$

On substitution,

$$(m_o^2c^2)c^2 = m_o^2c^4 + 2h(\upsilon-\upsilon')\,m_oc^2 - 2\,h^2vv'\,(1-\cos\phi)$$

$$m_o^2c^4 = m_o^2c^4 + 2h(\upsilon-\upsilon')\,m_oc^2 - 2\,h^2vv'\,(1-\cos\phi)$$
$$0 = 2h(\upsilon-\upsilon')\,m_oc^2 - 2\,h^2vv'\,(1-\cos\phi)$$
$$2h(\upsilon-\upsilon')\,m_oc^2 = 2\,h^2vv'\,(1-\cos\phi)$$
$$(\upsilon-\upsilon')\,m_oc^2 = hvv'\,(1-\cos\phi)$$

$$\frac{(\upsilon-\upsilon')}{\upsilon\upsilon'} = \frac{h}{m_oc^2}\,(1-\cos\phi)$$

$$\frac{1}{\upsilon'} - \frac{1}{\upsilon} = \frac{h}{m_oc^2}\,(1-\cos\phi)$$

$$\frac{c}{\upsilon'} - \frac{c}{\upsilon} = \frac{h}{m_o c}(1 - \cos\phi)$$

$$\lambda' - \lambda = \frac{h}{m_o c}(1 - \cos\phi)$$

$$\lambda' = \lambda + \frac{h}{m_o c}(1 - \cos\phi)$$

From the above equation it is clear that the wavelength of scattered radiation is greater than incident radiation

Therefore, Compton shift is given by

$$d\lambda = \lambda' - \lambda = \frac{h}{m_o c}(1 - \cos\phi)$$

Special cases:

$$if\ \phi = 0, then\ d\lambda = \lambda' - \lambda = \frac{h}{m_o c}(1 - \cos 0) = \frac{h}{m_o c}(1 - 1) = 0$$

$$if\ \phi = 90, then\ d\lambda = \lambda' - \lambda = \frac{h}{m_o c}(1 - \cos 90) = \frac{h}{m_o c}(1 - 0) = \frac{h}{m_o c}$$

$$if\ \phi = 180, then\ d\lambda = \lambda' - \lambda = \frac{h}{m_o c}(1 - \cos 180) = \frac{h}{m_o c}(1 - (-1)) = \frac{2h}{m_o c}$$

## WAVES AND PARTICLES:

Wave is a disturbance that propagates through space and time, usually with transference of energy. Wave's travel and transfer energy from one point to another, often with little or no permanent displacement of the particles of the medium. it is specified by its frequency, wave length, phase or wave velocity, amplitude and intensity.

A particle has mass and it is located at some definite point. The particle is specified by its mass, velocity, momentum, energy. A subatomic particle is an elementary or composite particle smaller than an atom. Particle physics and nuclear physics are concerned with the study of these particles.

## MATTER WAVES:-

In 1924, Louis de- Broglie suggested that matter has dual nature. Matter might exhibit wave like properties under approximate conditions.

Louis debroglie led to the concept of matter waves by considering the following.

- Since radiations has been shown to possess dual nature. Matter must also possess dual nature.
- Radiation is supplemented with particle characteristics to explain optical phenomenon, such as photo electric effect.

On similar lines material particles have to be supplemented with a wave aspect for understanding their behaviour. Based on the above concepts, debroglie made a bold suggestion in his doctorate thesis and presented the new idea of matter waves. For this he was honoured with the award of noble prize in 1929.

## DE-BROGLIE HYPOTHESIS:

In 1924, de-Broglie extended dual nature to material particles or micro particles like electrons, protons, neutrons etc. according to his hypothesis, when particles are accelerated then they will spread like a wave with a certain wave length.

He gave simple mathematical equations to support his hypothesis as follows:

The dual nature of matter was explained by combining Planck's equation for energy of a photon,

$E = h\vartheta$

And Einstein's mass and energy relation $E = mc^2$

$$mc^2 = h\vartheta$$

We know that velocity of light, $c = \vartheta\lambda$

Therefore, $h\frac{c}{\lambda} = mc^2$

$$\lambda = \frac{h}{mc} = \frac{h}{P}$$

The above equation indicates that a photon is associated with a momentum ‘P’.

Consider a particle of mass m, moving with a velocity v is associated with a wave called matter wave of wavelength$\lambda$, given by

$$\lambda = \frac{h}{mv}$$

This is known as de-Broglie wave length.

If E is the kinetic energy of the material particle, then

$$E = \frac{1}{2} mv^2$$

$$= \frac{(mv)^2}{2m}$$

$$= \frac{(P)^2}{2m}$$

Therefore, $P = \sqrt{2mE}$

Hence, de-Broglie wavelength,

$$\lambda = \frac{h}{P} = \frac{h}{\sqrt{2mE}}$$

deBroglie wavelength associated with electrons:

Let us consider the case of electrons of rest mass $m_0$ and charge ‘e’ being accelerated by potential ‘V’ volts.

$$\frac{1}{2} m_0 v^2 = eV$$

$$v = \sqrt{\frac{2eV}{m_0}}$$

Therefore, debroglie wavelength

$$\lambda = \frac{h}{m_0 v} = \frac{h}{m_0\sqrt{\frac{2eV}{m_0}}}$$

$$\lambda = \frac{h}{\sqrt{2em_0V}} = \frac{12.26}{\sqrt{V}} A^0$$

## CHARACTERISTICS OF MATTER WAVES:

Since,

$$\lambda = \frac{h}{mv} = \frac{h}{P}$$

- Lighter the particle, greater is the wavelength associated with it.
- Lesser the velocity of particle, longer the wavelength associated with it.
- For $v$=0,$\lambda$ =∝. This means that only with moving particles matter waves are associated.
- Whether the particle is charged or not, matter wave is associated with it.
- Matter waves can travel faster than light.

$$w = \frac{c^2}{v} = \left(\frac{1}{v}\right) c^2$$

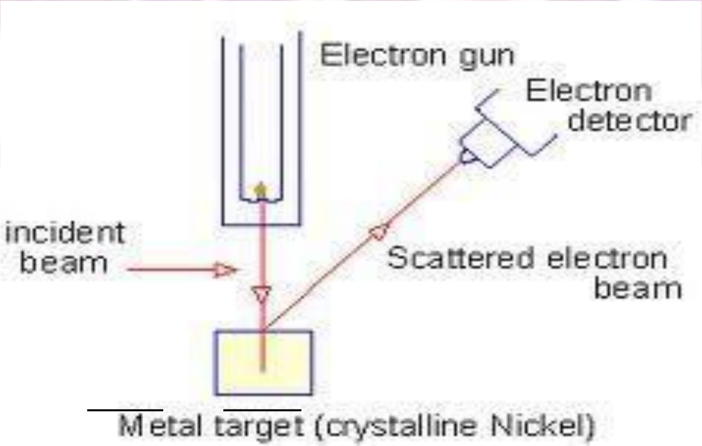
- Particle and wave nature cannot be exhibited simultaneously.

## EXPERIMENTAL STUDY OF MATTER WAVES:-

In 1927, Davisson and germer in the United States and in 1928 Thomson proved experimentally the existence of matter waves. They demonstrated that streams of electrons are diffracted when they are scattered from crystals. Also, stern and others showed the existence of matter waves in connection with molecular and atomic beams.

## GERMER-DAVISSON EXPERIMENT:

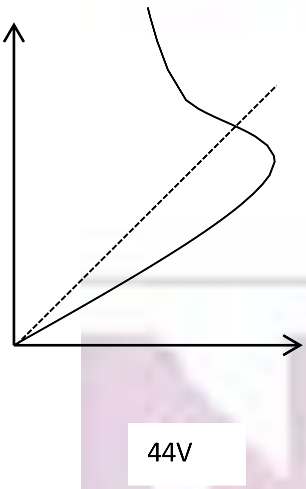
### Experimental arrangement:

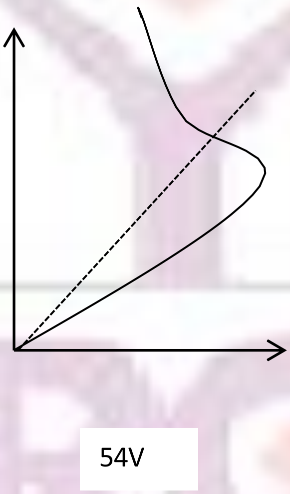


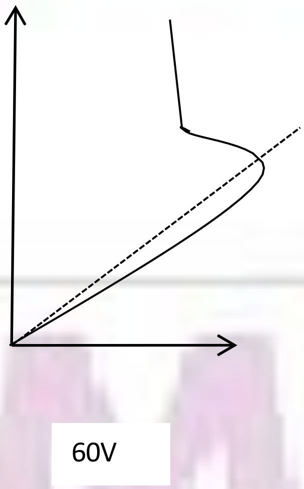
The experimental arrangement consists of an electron gun G where the electrons are produced and obtained in a fine beam by passing them through slits $s_1$and $s_2$. The beam of electrons is directed to fall on a large single crystal nickel, known as target T. the electrons acting the waves, are diffracted in different directions. The angular distribution is measured by an ionisation chamber ‘c’ which is connected to galvanometer. The chamber can moves on a circular graduated scale ‘s’ between 29 to 90 degrees to receive the reflected electrons. A retarding potential is maintained in the chamber so that only fast moving electrons coming from electron gun may enter inside it.

The secondary electrons (slow electrons) produced by collisions with atoms from nickel target are reflected by ionisation chamber. In this way the galvanometer deflection is only due to electrons coming from electron gun.

For a particular accelerating potential ‘V’, the ionisation chamber is moved to various positions on the scale s and galvanometer current is noted for each position. A graph is then plotted between galvanometer current against angle Ɵ between incident beam and beam entering the cylinder. The observations are repeated for different accelerating potentials.







It is observed that a bump begins to appear in the curve for 44 V electrons.

- ✓ With increasing potential, the bump moves upwards.
- ✓ The bump becomes most prominent in the curve for 54 V electrons at Ɵ=50
- ✓ At higher potentials, the bumps gradually disappear.

According to de-Broglie, the wavelength associated with electron accelerated through a potential V is given by

$$\lambda = \frac{12.26}{\sqrt{V}} A^0$$

For V=54 V,

$$\lambda = \frac{12.26}{\sqrt{54}} A^0$$

$$\lambda = 1.67\ A^0$$

From X-ray analysis, for nickel crystal d=0.1$A^0$. According to experiment, θ=50. Corresponding angle of incidence relative to the Bragg plane is

$$\theta' = \frac{180 - 50}{2} = 65^0$$

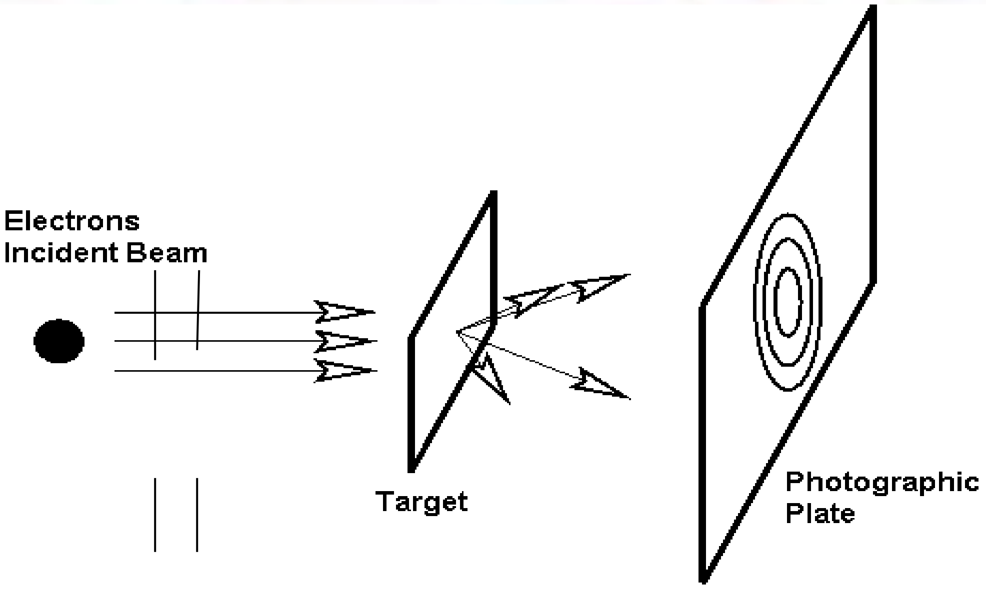
Therefore, for n=1$\lambda = 2d\ \sin\theta = 1.69\ A^0$

This is the good agreement with the wavelength from de-Broglie hypothesis. Since two values are coincided, hence confirms the de-Broglie concept of matter waves.

## G-P THOMSON EXPERIMENT:-

G-P Thomson performed experiments with electrons accelerated from 10,000 to 50,000 volts. In these experiments, Thomson observed diffraction patterns and determined the wavelengths of electrons.

His experimental arrangement is as shown.



The high energy electron beam is produced by cathode ‘c’ which is accelerated to a potential 50,000 volts. A fine beam is obtained by passing it through the slit s. the accelerated fine beam of electrons now falls on a thin film G of gold. The photograph of the beam from the foil is recorded on a photographic plate P.

After developing the plate, a pattern consisting of concentric rings about a central spot is obtained which is similar as produced by X-rays.

To be sure, that this pattern is due to electrons or X-rays, the cathode rays in the tube are deflected by magnetic field. It was observed that beam shifts correspondingly showing thereby that the pattern is produced by electrons and not by X-rays.

As the diffraction pattern can only be produced by waves and not by the particles, so Thomson concluded that electrons behave like waves. The wavelengths obtained by diffraction patterns agrees well with the wavelength’s obtained by de Broglie relations.

Thus Thomson experiments clearly demonstrated the existence of matter waves.

## SCHRODINGER WAVE EQUATION:

Schrodinger in 1926 developed a wave equation for the moving particles. If a particle of mass ‘m’ moving with a velocity v is associated with a group of waves.

Let $\varphi$ be the wave function of the particle

$\varphi = \varphi_o \sin(\omega t - Kx)$.......... (1)

where K=$\frac{2\pi}{\lambda}$

Differentiating twice the eq. (1)

$\frac{\partial^2\varphi}{\partial x^2} = -K^2\varphi_o \sin(\omega t - Kx) = -K^2\varphi$ ................... (2)

$$\frac{\partial^2\varphi}{\partial x^2} + K^2\varphi = 0$$

$$\frac{\partial^2\varphi}{\partial x^2} + \frac{4\pi^2}{\lambda^2}\varphi = 0 \dots\dots\dots(3)$$

From de-Broglie wavelength, $\lambda = \frac{h}{mv} \dots\dots\dots..(4)$

From (3) & (4),

$\frac{\partial^2\varphi}{\partial x^2}+\frac{4\pi^2m^2v^2}{h^2}\varphi=0\ \ldots\ldots\ldots\ (5)$

If E is total energy and K & V are kinetic and potential energies then

$$E=K+V$$

$$K=E-V$$

$$\frac{1}{2}mv^2=E-V$$

$m^2v^2=2m(E-V)\ \ldots\ldots\ldots.(6)$

From (5) & (6)

$$\frac{\partial^2\varphi}{\partial x^2}+\frac{4\pi^2}{h^2}2m(E-V)\varphi=0$$

$$\frac{\partial^2\varphi}{\partial x^2}+\frac{8\pi^2}{h^2}m(E-V)\varphi=0$$

Since, $\hbar=\frac{h}{2\pi}$. The above equation becomes,

$\frac{\partial^2\varphi}{\partial x^2}+\frac{2}{\hbar^2}m(E-V)\varphi=0\ \ldots\ldots\ldots(7)$

This is the Schrodinger wave equation in 1-D.

For 3-D,

$\frac{\partial^2\varphi}{\partial x^2}+\frac{\partial^2\varphi}{\partial y^2}+\frac{\partial^2\varphi}{\partial z^2}+\frac{8\pi^2}{h^2}m(E-V)\varphi=0\ \ldots\ldots\ldots.(8)$

Using laplacian operator, $\nabla^2=\frac{\partial^2}{\partial x^2}+\frac{\partial^2}{\partial y^2}+\frac{\partial^2}{\partial z^2}$

From (8)

$$\nabla^2\varphi+\frac{2}{\hbar^2}m(E-V)\varphi=0$$

This is the Schrodinger wave equation. Since time factor doesn't appear in the above equation this is called Schrodinger time independent equation.

## PHYSICAL SIGNIFICANCE OF$\varphi$:-

The wave function $\varphi$ has no direct physical meaning. To explain the relation of particle to wave packet Max Born proposed the physical significance of $\varphi$. According to Born $\varphi\varphi^* = |\varphi|^2$ gives the probability of finding the particle in the state$\varphi$. That is $\varphi^2$ is a measure of probability density. For the total probability of finding the particle somewhere is

$\iiint |\varphi|^2 dx\, dy\, dz = 1$.

$\varphi$ Satisfying above requirements is said to be normalised.

Besides normalisation, the wave function $\varphi$ must fulfil the following requirements.

- It must be finite everywhere.

  If it is infinite at a particular point, then pbb. of finding the particle at that point is infinitely large. This is not possible. Hence, $\varphi$ must be finite or zero value at any point.

- It must be single valued:
  If it is multi valued then finding a particle at a point will have more value. It is not possible.
- It must be continuous:
  For Schrodinger equation $\frac{\partial^2\varphi}{\partial x^2}$ must be finite everywhere. This is possible only when $\frac{\partial\varphi}{\partial x}$ is continuous. Which means that $\varphi$ is continuous.

## PARTICLE IN ONE DIMENSIONAL POTENTIAL BOX:-

Consider a particle of mass 'm' moving along X-axis between the two rigid walls A and B at x=0 and x=a. the particle is free to move between the walls. The potential energy is constant between the walls because no force is acting on the particle.

Since the particle strikes the walls and get reflected back. So, the force acting on the particle abruptly changes from zero to a finite value F with in a distance of zero at the wall. We know that$|F| = \frac{\partial V}{\partial x}$. Therefore, $\Delta V \to 0\ as\ \Delta x \to\propto such\ that\ \frac{\partial V}{\partial x}$has a finite value.

So, potential energy of particle becomes infinite at the walls. Therefore,

$$V(x) = \propto \qquad for\ x < 0\ and\ x > a$$

$$V(x) = 0 \qquad for\ 0 \le x \le a$$

The Schrodinger wave equation for particle is given by

$$\frac{\partial^2\varphi}{\partial x^2} + \frac{8\pi^2}{h^2} m(E - V)\varphi = 0$$

As V=0 between the walls,

$$\frac{\partial^2\varphi}{\partial x^2} + \frac{8\pi^2}{h^2} m(E)\varphi = 0$$

Let $\frac{8\pi^2}{h^2} m(E) = K^2$. Therefore,

$$\frac{\partial^2\varphi}{\partial x^2} + K^2\varphi = 0$$

The solution of above equation is

$$\varphi(x) = A\sin Kx + B\cos Kx$$

Where A & B are constants, which are obtained by applying the boundary conditions.

$$\varphi = 0\ at\ x = 0, x = a$$

- $\varphi = 0\ at\ x = 0$

$$0 = A\sin 0 + B\cos 0$$
$$\rightarrow B = 0$$
$$\varphi(x) = A\sin Kx$$

- $\varphi = 0\ at\ x = a$

$$0 = A\sin Ka$$

Either A=0 or $\sin Ka = 0\ but\ A \neq 0$

Because if A=0, the entire function will be zero as B=0.

Therefore, $\sin Ka = 0$

Ka=n$\pi$

K=$\frac{n\pi}{a}$

Therefore wave function becomes,

$$\varphi(x) = A\sin\frac{n\pi}{a}x$$

We know that

$$K^2 = \left(\frac{\mathrm{n}\pi}{a}\right)^2 \ \& \ \frac{8\pi^2}{h^2} m(E) = K^2.$$

Therefore,

$$\left(\frac{\mathrm{n}\pi}{a}\right)^2 = \frac{8\pi^2}{h^2} m(E)$$

$$E_n = \frac{n^2h^2}{8ma^2}$$

From the above equation it is clear that the particle can have only discrete set of values of energy. That is energy is quantised.

$$E_1 = \frac{h^2}{8ma^2}, for\ n = 1$$

$$E_2 = \frac{4h^2}{8ma^2}, for\ n = 2$$

$$E_n = n^2E_1$$

The value of A can be obtained by applying normalisation condition given in below equation

$$\iiint |\varphi|^2 dx\, dy\, dz = 1.$$

Since the particle is inside the box of length ‘a’, the pbb. of finding the particle inside the box is unity.

$$\int_0^a |\varphi|^2 dx = 1$$

$$\int_0^a \left(A \sin\frac{\mathrm{n}\pi}{a} x\right)^2 dx = 1$$

$$A^2 \int_0^a \frac{1}{2}\left[1 - \cos\frac{2n\pi x}{a}\right] dx = 1$$

$$\frac{A^2}{2}\left[x - \frac{a}{2n\pi}\sin\frac{2n\pi x}{a}\right] = 1$$

$$\frac{A^2a}{2} - 0 = 1$$

$$A = \sqrt{\frac{2}{a}}$$

The normalised wave function is

$$\varphi_n(x) = \sqrt{\frac{2}{a}}\ \sin \frac{\mathrm{n}\pi}{a} x$$

The wave function $\varphi_n$ and corresponding energies$E_n$, which are often called eigen function and Eigen values respectively.

The Eigen function in 3-d potential well is

$$\varphi_n = \left(\frac{8}{L^3}\right)^{1/2} \sin K_1 x\ \sin K_2 y\ \sin K_3 z$$

Where$K_1 = \frac{n_1\pi}{a}$,$K_2 = \frac{n_2\pi}{a}$, $K_3 = \frac{n_3\pi}{a}$

And Eigen value is

$$E_n = \frac{n^2h^2}{8ma^2}$$

Where, $n^2 = n_1^2 + n_2^2 + n_3^2$

Where three integers $n_1, n_2, n_3$ are called quantum numbers. $n_1, n_2, n_3$are never be zero, since $\varphi$ is not zero.

# UNIT-2

# SEMICONDUCTOR PHYSICS

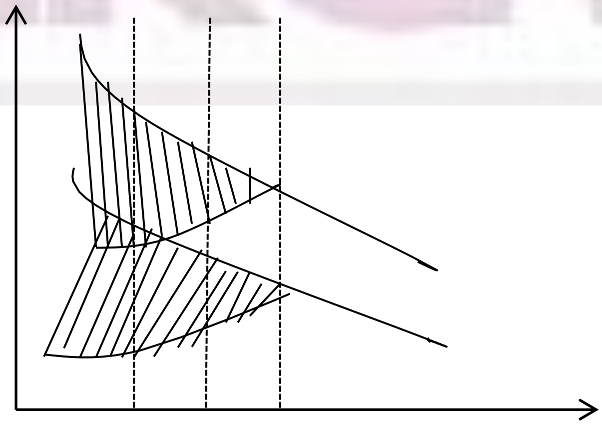
## ENERGY BANDS OF SOLIDS:-

In an isolated atom, the electrons are tightly bound and have discrete, sharp energy levels. A metal or any solid contains a large no. of atoms. These are very close to each other. As the interatomic distance decreases, the allowed energy levels of electron of one atom overlaps with those of neighbouring atoms. Hence in a solid the energy level corresponding to any one quantum no. splits up into many closely spaced levels, thus forming a band of energy.

The width of this band depends on the degree of overlap of electrons of adjacent atoms and is largest for the outermost atomic electrons.

The electrons in the lower energy bands are of no importance in determining electrical properties of solids. Hence, the electrons in the outermost bands of solids are important in determining many of the physical properties of solids. Therefore, the allowed energy bands are valence and conduction bands. The band corresponding to outer most orbit is called conduction band next inner band is called valence band. The energy gap between these two allowed bands is called forbidden energy gap. In this gap, electrons cannot have energy values.

Valence band is occupied by valence electrons and conduction band which is vacant at 0 K. according to the width of the gap between the bands and band occupation by electrons, all solids can be classified broadly in to three groups, namely metals, semiconductors and insulators.



## CLASSIFICATION OF SOLIDS:-

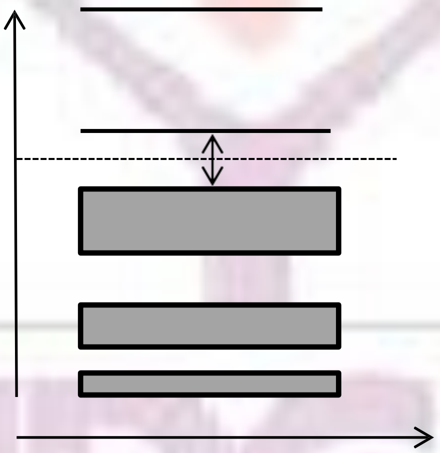
In solids the gap between the two outer most allowed energy bands depends on the equilibrium spacing between the atoms.

As $r_0$ decreases the band gap also decreases.

**Insulators:** if the energy band gap is wide enough, say of the order of 5-10 eV, then it is virtually impossible at all the practical temperatures to thermally excite an appreciable no. of electrons across this gap from the top of the highest filled band to the bottom of the lowest empty band.

All bands are then either completely filled or empty at any temperature and therefore an external electric field cannot cause any current. All solids, elements and compounds having this character of bonding and thus zero conductivity, are classified as insulators.

**Eg:** - diamond with a band gap, 7eV.



**Semiconductors: -** if the band gap between the highest filled and the lowest empty bands is quite small, say of the order 1 eV or less, then there will be an appreciate no. of electrons that will be excited thermally from states near the top of the filled band to states near the bottom of the next empty band across the band gap.

**Eg:** germanium with energy gap 0.78 eV, silicon with energy gap 1.21 eV.

All semiconductors become insulators as the temperature approaches absolute zero. At sufficiently high temperatures, all insulators must exhibit semiconductor behaviour.

**Conductors:-** solids which are having a great no. of the free electrons in the outer most valence band which is partially filled, then those solids are called conductors. They conduct electricity at all temperatures. The electrical conductivity of a conductor is much larger than that of a semiconductor due to its large concentration of free electrons.

## SEMICONDUCTORS:-

A semiconductor is a solid having a fully filled valence band which is separated from an empty conduction band by a forbidden gap at absolute zero. This gap is usually quite narrow in semiconductors so that at finite temperatures some of the electrons of the filled valence band are always excited across this gap in to the conduction band where they become free. Further as the temperature increases, more and more electrons are free in this manner. Hence, in these materials, it is possible to control the carrier concentration.

On the other hand, in metals and insulators such a control is not possible by any means. The mechanism that provide and control the free charge carrier concentration in semiconductors will be classified into two broad categories.

1. Thermal effects: at a finite temperature there is a certain no. of electrons that is excited from the filled valence band to the empty conduction band, and as the temperature is increased this number is also increased.

   An electron so exited leaves holes behind in the valence band. Both, the electrons in the conduction band and the holes in the valence band can act as charge carriers.

2. Introduction of certain impurities in to the pure semiconductors: a suitable highly doped semiconductor at low temperatures will bring about a change in the charge carrier concentration. The properties of such semiconductors are therefore controllable by the nature and amount of impurities added. Such semiconductors are classified as the extrinsic semiconductors.

   In pure semiconductors, the primary mechanism that brings a change in charge carrier concentration arises from the valence band to conduction band. Obviously their properties are determined by the inherent nature of the elements themselves. Such semiconductors are classified as the pure or intrinsic semiconductors.

## INTRINSIC SEMICONDUCTORS:

The band structure of intrinsic semiconductors at 0 K is not unlike to that of insulators. There is a vacant conduction band separated by an energy gap $E_g$ from a filled valence band.

At absolute zero, the electric conduction is not possible. But as the temperature is increased, the electrons are thermally excited from the valence band to the conduction band. Where they become free and the conduction is possible. Hence, the electron-hole pairs are created. The no. of electrons in the conduction band will be equal to the no. of holes in the valence band.

### Calculation of density of electrons and holes: -

Let dn be the no. of electrons available between energy interval E and E+dE in the conduction band.

$$dn = Z(E)F(E)dE$$

$Z(E)dE -$Density of states in the interval E &E+dE.

F(E)-pbb. that a state of energy E is occupied by an electron.

If $E_c$ is the energy corresponding to the bottom of the conduction band then,

$$n = \int dn = \int_{E_c}^{\infty} Z(E)F(E)dE$$

[Since pbb. of electrons occupying the upper levels of conduction band reduces to zero at infinity].

We know that density of states between energy interval E and E+dE is given by

$$Z(E)dE = \frac{4\pi}{h^3}(2m)^{3/2}E^{1/2}\ dE$$

Since electron is moving in a periodic potential, its mass has to be replaced by its effective mass$m_e^*$.

$$Z(E)dE = \frac{4\pi}{h^3}(2m_e^*)^{3/2}E^{1/2}\ dE$$

Since the energy E starts at the bottom of the conduction band$E_c$,

$$Z(E)dE = \frac{4\pi}{h^3}(2m_e^*)^{3/2}(E - E_c)^{1/2}\ dE$$

Pbb. of an electron occupying an energy state E is given by

$$F(E) = \frac{1}{1 + e^{(E - E_F/KT)}}$$

$$F(E) = e^{((E_F - E/KT))}$$

Therefore,

$$n = \int_{E_c}^{\infty} \frac{4\pi}{h^3}(2m_e^*)^{3/2}(E - E_c)^{1/2}e^{((E_F - E/KT))}\ dE$$

$$= \frac{4\pi}{h^3}(2m_e^*)^{3/2}\int_{E_c}^{\infty}(E - E_c)^{1/2}e^{((E_F - E/KT))}\ dE$$

$$= \frac{4\pi}{h^3}(2m_e^*)^{3/2}[e^{E_F/KT}]\int_{E_c}^{\infty}(E - E_c)^{1/2}e^{((-E/KT))}\ dE$$

To solve this integral, let us point

$$E - E_c = x, \qquad E = x + E_c \qquad dE = dx$$

$$n = \frac{4\pi}{h^3}(2m_e^*)^{3/2}[e^{E_F/KT}]\int_0^{\infty}(x)^{1/2}e^{(-\frac{(E_c + x)}{KT})}\ dx$$

$$= \frac{4\pi}{h^3}(2m_e^*)^{3/2}[e^{(E_F - E_c)/KT}]\int_0^{\infty}(x)^{1/2}e^{(-\frac{(x)}{KT})}\ dx$$

Using gamma functions,

$$\int_0^{\infty}(x)^{1/2}e^{(-\frac{(x)}{KT})}\ dx = (KT)^{3/2}\frac{\pi^{1/2}}{2}$$

Therefore,

$$n = \frac{4\pi}{h^3}(2m_e^*)^{3/2}[e^{(E_F-E_c)/KT}](KT)^{3/2}\ \frac{\pi^{1/2}}{2}$$

That is no. of electrons per unit volume of the material is given by

$$n = 2\left[\frac{2\pi m_e^* KT}{h^2}\right]^{3/2} exp\left[\frac{(E_F - E_c)}{KT}\right]$$

Similarly no. of holes per unit volume of the material is given by

$$p = 2\left[\frac{2\pi m_h^* KT}{h^2}\right]^{3/2} exp\left[\frac{(E_v - E_F)}{KT}\right]$$

**Intrinsic carrier concentration:-**

In intrinsic semiconductor,

n=p

Hence n=p=$n_i$ is called intrinsic carrier concentration. Therefore,

$$n_i^2 = np = 4\left[\frac{2\pi KT}{h^2}\right]^3 (m_e^* m_h^*)^{3/2} exp\left[\frac{(E_v - E_c)}{KT}\right]$$

$$= 4\left[\frac{2\pi KT}{h^2}\right]^3 (m_e^* m_h^*)^{3/2} exp\left[\frac{(-E_g)}{KT}\right]$$

Where $(E_v - E_c) = E_g$ is the forbidden energy gap.

Hence,

$$n_i = 2\left[\frac{2\pi KT}{h^2}\right]^{3/2} (m_e^* m_h^*)^{3/4} exp\left[\frac{(-E_g)}{2KT}\right]$$

**Fermi level:**

Since n=p in intrinsic semiconductor,

$$2\left[\frac{2\pi m_e^* KT}{h^2}\right]^{3/2} exp\left[\frac{(E_F - E_c)}{KT}\right] = 2\left[\frac{2\pi m_h^* KT}{h^2}\right]^{3/2} exp\left[\frac{(E_v - E_F)}{KT}\right]$$

$$(m_e^*)^{3/2}\ exp\ [\frac{(E_F - E_c)}{KT}] = (m_h^*)^{3/2}\ exp\ [\frac{(E_v - E_F)}{KT}]$$

$$\exp\ [\frac{2E_F}{KT}] = (\frac{m_h^*}{m_e^*})^{3/2}\ exp\ (\frac{(E_v + E_c)}{KT})$$

Taking log on both sides

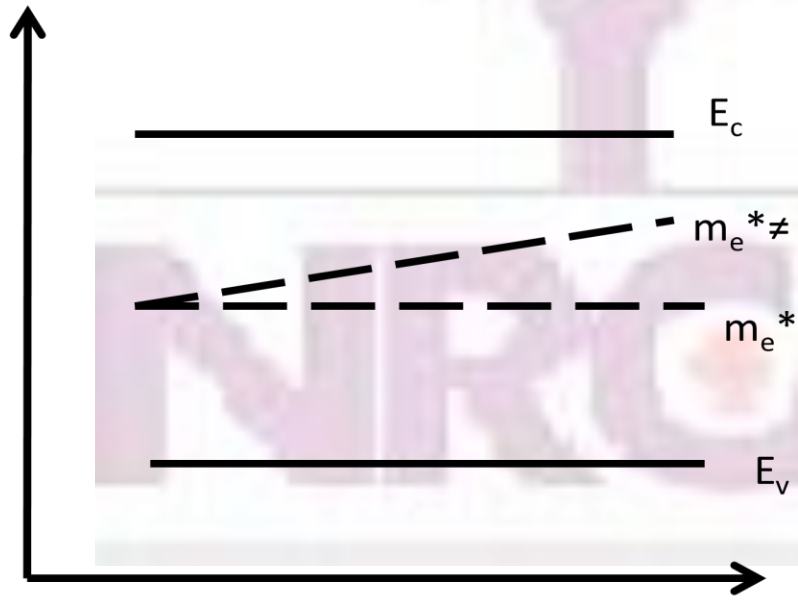
$$[\frac{2E_F}{KT}] = \frac{3}{2}\ log\ (\frac{m_h^*}{m_e^*}) + (\frac{(E_v + E_c)}{KT})$$

$$E_F = \frac{3KT}{4}\ log\ (\frac{m_h^*}{m_e^*}) + (\frac{(E_v + E_c)}{2})$$

If we assume, $m_e^* = m_h^*$. Then

$$E_F = (\frac{(E_v + E_c)}{2})$$

Thus, Fermi level is located half way between the valence band and conduction bands and its position is independent of temperature.



Since $m_h^*$ is greater than $m_e^*$, $E_F$ is just above the middle and rises slightly with increasing temperature.

## EXTRINSIC SEMICONDUCTOR:-

A semiconducting material in which the charge carrier originates from impurity atoms added to the material is called impurity semiconductor or extrinsic semiconductor.

The electrical properties of pure semiconductors are drastically modified by addition of certain impurities.

Eg: - addition of boron to silicon in the proportion of 1 boron atom to $10^5$ silicon atoms increases the conductivity of pure silicon by a factor $10^3$at room temperature.

There are two types of impurities possible.

**n- Type semiconductor:**

Pentavalent elements which are having 5 electrons in its outermost orbit are added to an intrinsic semiconductor in small trace, then the semiconductor formed is called n- type semiconductor.

Out of 5 electrons of the impurity 4 electrons are bounded to the germanium atoms and 1 electron is left free which is weakly bonded to the atom.

Even for lesser thermal energy, this fifth electron is released leaving the parent atom positively ionised. In the energy level diagram, the energy level of the fifth electron is called donor level which is very close to the conduction band. The electron in donor level gets excited to conduction band at room temperature only.

Hence, majority charge carriers in n-type semiconductor are electrons and holes are minority charge carriers.

**P-type semiconductor:**

Trivalent elements which are having 3 electrons in its outer most orbits are added to an intrinsic semiconductor in small trace, then the semiconductor formed is called p-type semiconductor.

All the three electrons in In (indium) are engaged in covalent bonding with three neighbouring Ge atoms. In needs one more electron to complete its bond. Since In accepts one extra electron to complete the bond, the energy level of this impurity atom is called acceptor level.

This acceptor level lies just above the valence band. Even at relatively low temperatures, the acceptor atoms get ionised taking electron from valence band and thus giving rise to the holes in valence band for conduction.

Hence, majority charge carriers in p-type semiconductor are holes in valence band and minority charge carriers are electrons.

**Carrier Concentration in N-Type Semiconductor:-**

Let $N_d$ is the donor concentration, the number of atoms per unit volume of the material and $E_d$ is the donor energy level. At very low temperatures all donor levels are filled with electrons.

With increase of temperature more and more donor atoms get ionised and the density of electrons in the conduction band increases.

Density of electrons in conduction band is given by

$$n = 2\left[\frac{2\pi m_e^* KT}{h^2}\right]^{3/2} exp\left[\frac{(E_F - E_c)}{KT}\right] \ldots\ldots\ldots\ldots\ldots (1)$$

The density of ionised donors is given by

$$N_d[1 - F(E_d)] = N_d \exp\left(\frac{E_d - E_F}{KT}\right) \ldots\ldots\ldots\ldots\ldots (2)$$

At very low temperatures, no. of electrons in conduction band must be equal to the no. of ionised donors.

$$2\left[\frac{2\pi m_e^* KT}{h^2}\right]^{3/2} exp\left[\frac{(E_F - E_c)}{KT}\right] = N_d \exp\left(\frac{E_d - E_F}{KT}\right) \ldots\ldots\ldots\ldots (3)$$

$$exp\left[\left(\frac{E_F - E_c}{KT}\right) - \left(\frac{E_d - E_F}{KT}\right)\right] = \frac{N_d}{2\left[\frac{2\pi m_e^* KT}{h^2}\right]^{3/2}}$$

$$exp\left[\left(\frac{2E_F - (E_c + E_d)}{KT}\right)\right] = \frac{N_d}{2\left[\frac{2\pi m_e^* KT}{h^2}\right]^{3/2}}$$

Take log on both sides

$$\left[\left(\frac{2E_F-(E_c+E_d)}{KT}\right)\right] = \log \frac{N_d}{2\left[\frac{2\pi m_e^* KT}{h^2}\right]^{3/2}}$$

$$E_F = \left(\frac{E_c+E_d}{2}\right) + \frac{KT}{2}\log\left(\frac{N_d}{2\left[\frac{2\pi m_e^* KT}{h^2}\right]^{3/2}}\right) \ldots\ldots\ldots\ldots\ldots..(4)$$

At o K

$$E_F = \left(\frac{E_c+E_d}{2}\right) \ldots\ldots\ldots\ldots (5)$$

At 0 K, Fermi level lies exactly at the middle of the donor level $E_d$ and bottom of the conduction band $E_c$.

From equation (1)

$$n = 2\left[\frac{2\pi m_e^* KT}{h^2}\right]^{3/2} exp\left[\frac{(E_F - E_c)}{KT}\right]$$

Substituting (4) in above equation.

$$exp\left[\frac{(E_F - E_c)}{KT}\right] = \exp\left[\frac{\frac{E_c+E_d}{2} + \frac{KT}{2}\log\left(\frac{N_d}{2\left[\frac{2\pi m_e^* KT}{h^2}\right]^{3/2}}\right)}{KT}\right]$$

$$= \exp\left[\frac{E_d - E_c}{2KT} + \frac{1}{2}\log\left(\frac{N_d}{2\left[\frac{2\pi m_e^* KT}{h^2}\right]^{3/2}}\right)\right]$$

$$= \exp\left(\frac{E_d - E_c}{2KT}\right)\exp\left(\frac{1}{2}\log\left(\frac{N_d}{2\left[\frac{2\pi m_e^* KT}{h^2}\right]^{3/2}}\right)\right)$$

$$= \exp\left(\frac{E_d - E_c}{2KT}\right)\left(\frac{N_d}{2\left[\frac{2\pi m_e^* KT}{h^2}\right]^{3/2}}\right)^{1/2}$$

Hence,

$$n = 2\left[\frac{2\pi m_e^* KT}{h^2}\right]^{3/2} \exp\left(\frac{E_d - E_c}{2KT}\right)\left(\frac{N_d}{2\left[\frac{2\pi m_e^* KT}{h^2}\right]^{3/2}}\right)^{1/2}$$

$$n = (2N_d)^{1/2}\left[\frac{2\pi m_e^* KT}{h^2}\right]^{3/4} \exp\left(\frac{E_d - E_c}{2KT}\right)$$

At low temperatures,

$$n \propto \sqrt{N_d}$$

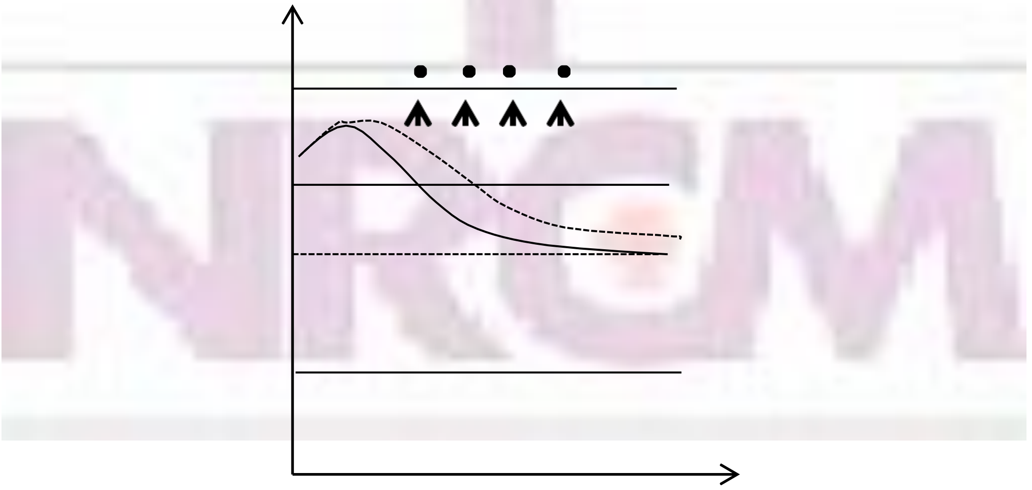
i.e., density of electrons is proportional to square root of donor concentration.

**Variation of Fermi level with temperature:-**

With increase of temperature $E_F$ increases slightly from equation (4). As the temperature increased more and more donor atoms are ionised. For a particular temperature all the donor atoms are ionised.

Further increase in temperature results in generation of electron- hole pair due to breaking of covalent bonds and material tends to behave in intrinsic matter.

The Fermi level gradually moves towards intrinsic Fermi level$E_i$.



**Variation of Fermi level with donor concentration:**The lowering of Fermi level from $E_F$ where $E_F = \frac{E_d+E_c}{2}$ to intrinsic Fermi level $E_i$ with the rise of temperature is slow in the case of higher donor concentration material than the lower one.

**Carrier Concentration in P-Type Semiconductor:-**

Let $N_a$ is the acceptor concentration, the number of atoms per unit volume of the material and $E_a$ is the acceptor energy level. At very low temperatures all acceptor levels are empty.

As the temperature increases acceptor atoms get ionised i.e., electrons from valence band move to vacant sites of acceptor level leaving holes in the valence band.

Density of holes in valence band is

$$p = 2\left[\frac{2\pi m_h^* KT}{h^2}\right]^{3/2} exp\left[\frac{(E_v - E_F)}{KT}\right] \ldots\ldots\ldots\ldots (1)$$

Since $E_F$ lies below the acceptor level, the density of ionised acceptors is given by

$$N_a[F(E_a)] = N_a \exp\left(\frac{E_F - E_a}{KT}\right) \ldots\ldots\ldots\ldots\ldots (2)$$

Density of holes in V.B = density of ionised acceptors.

$$2\left[\frac{2\pi m_h^* KT}{h^2}\right]^{3/2} exp\left[\frac{(E_v - E_F)}{KT}\right] = N_a \exp\left(\frac{E_F - E_a}{KT}\right)$$

$$\exp\left[\frac{E_v + E_a}{KT} - \frac{2E_F}{KT}\right] = \frac{N_a}{2\left[\frac{2\pi m_h^* KT}{h^2}\right]^{3/2}} \ldots\ldots\ldots\ldots\ldots (3)$$

Taking log on both sides

$$E_F = \left(\frac{E_v + E_a}{2}\right) - \frac{KT}{2}\log\left(\frac{N_a}{2\left[\frac{2\pi m_h^* KT}{h^2}\right]^{3/2}}\right) \ldots\ldots\ldots\ldots (4)$$

At 0 k $E_F = \left(\frac{E_v+E_a}{2}\right) \ldots\ldots\ldots\ldots\ldots (5)$

At 0 k Fermi level lies at the middle of the acceptor level and top of the valence band.

Substituting (4) in (1)

$$p = 2\left[\frac{2\pi m_h^* KT}{h^2}\right]^{3/2} exp\left[\frac{(E_v - E_F)}{KT}\right]$$

$$exp\left[\frac{(E_v - E_F)}{KT}\right] = \exp\left[\frac{E_v - \frac{E_v + E_a}{2} + \frac{KT}{2}\log\left(\frac{N_a}{2\left[\frac{2\pi m_h^* KT}{h^2}\right]^{3/2}}\right)}{KT}\right]$$

$$= \exp\left\{\left[\frac{(E_v - E_a)}{2KT}\right] + \log\left(\frac{N_a}{2\left[\frac{2\pi m_h^* KT}{h^2}\right]^{3/2}}\right)^{\frac{1}{2}}\right\}$$

$$= \exp\left[\frac{(E_v - E_a)}{2KT}\right]\left(\frac{N_a}{2\left[\frac{2\pi m_h^* KT}{h^2}\right]^{3/2}}\right)^{1/2}$$

Therefore,

$$P = 2\left[\frac{2\pi m_h^* KT}{h^2}\right]^{3/2} exp\left[\frac{(E_v - E_a)}{2KT}\right]\left(\frac{N_a}{2\left[\frac{2\pi m_h^* KT}{h^2}\right]^{3/2}}\right)^{1/2}$$

$$p = 2N_a^{1/2}\left[\frac{2\pi m_h^* KT}{h^2}\right]^{3/4} exp\left[\frac{(E_v - E_a)}{2KT}\right]$$

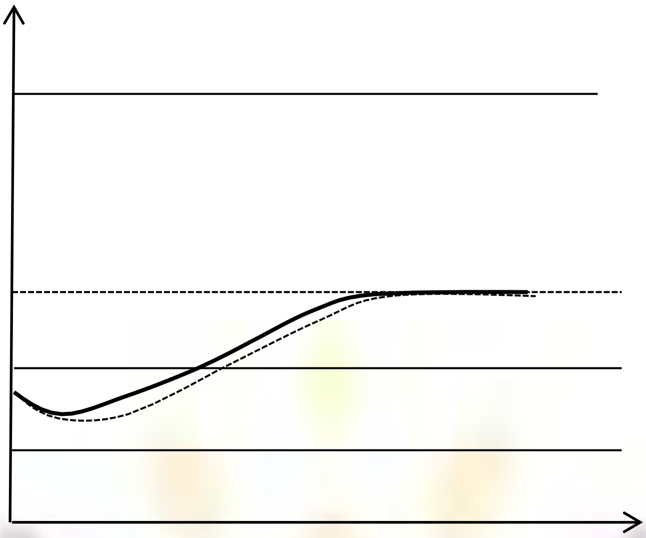
Therefore, $\rho \propto N_a^{1/2}$.

i.e., holes in valence band are directly proportional to square root of acceptor concentration.

**Variation of Fermi level with temperature:-**

With the increase of temperature, $E_F$ decreases slightly as per equation (4). As temperature is increased more and more acceptor atoms are ionised and at a particular temperature all acceptor atoms are ionised.

Further increase of temperature generates electron-hole pairs and material tends to behave as intrinsic semiconductor. The Fermi level gradually moves towards intrinsic Fermi level.



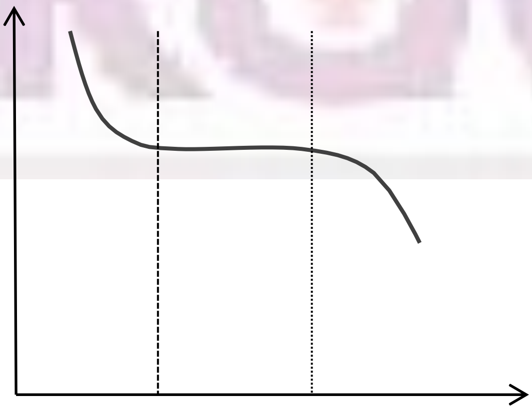
**Variation of Fermi level with carrier concentration:-**

The raising of Fermi level from $E_F$ when $E_F = (\frac{E_v+E_a}{2})$ to intrinsic Fermi level $E_i$ with rise of temperature is slow in case of highly doped one.

**Variation of Carrier Concentration With Temperature:-**

For an n-type semiconductor the variation of n and p with temperature is shown an above.

- At 0 K, conduction band and valence band are free from any charge carrier hence zero conductivity.
- With increase of temperature, donor atoms get ionised and electron concentration in conduction band increases until all the donor atoms are ionised. This region is called **impurity range**.
- During this process, Fermi level shifts towards donor level $E_d$ from the middle of $E_c$ and $E_d$.



- At about room temperature, all donor atoms get ionised. So, concentration of electron in conduction band remains constant for certain temperature range. This region is called **<u>exhaustion range.</u>** In this region, Fermi level crosses donor level.
- As the temperature is increased further, when thermal energy is sufficiently high, covalent bonds are broken and electron-hole pairs are formed. Hence, electron get excited to conduction band. Further increase of temperature more and more electrons from valence band reach conduction band and Fermi level moves down gradually until it reaches the middle of the forbidden gap. The material practically becomes intrinsic and so this region is called **<u>intrinsic range</u>**.

## DIFFUSION CURRENT AND DRIFT CURRENT:

The diffusion of carriers across the junction depends on the concentration of carriers across the junction.

The diffusion current density for electrons is

$$J_n(diffusion) = eD_n\frac{dn}{dx}$$

The diffusion current density for holes is

$$J_p(diffusion) = eD_p\frac{dp}{dx}$$

Where $\frac{dn}{dx}, \frac{dp}{dx}$ is concentration gradient.

And $D_n, D_p$ are electron and hole diffusion constants.

Due to diffusion of electrons from n-type to p-type leaves the region near the junction on n-side positively ionised forming positive space charge. Similarly, on p-side negatively ionised forming negative space charge region. Hence, $E_B$ is produced in a direction opposite to that of diffusion current. Hence, minority charge carriers drift from one side to another.

The current density due to electron drift

$$J_n(drift) = e\mu_n n E_B$$

The current density due to hole drift

$$J_p(drift) = e\mu_p p E_B$$

The total electron and hole current densities are given by

$$J_n(total) = J_n(diffusion) + J_n(drift)$$

$$J_n(total) = -eD_n\frac{dn}{dx} + e\mu_n n E_B$$

Similarly, $$J_p(total) = -eD_p\frac{dp}{dx} + e\mu_p p E_B$$

At equilibrium, the diffusion and drift current cancel each other.

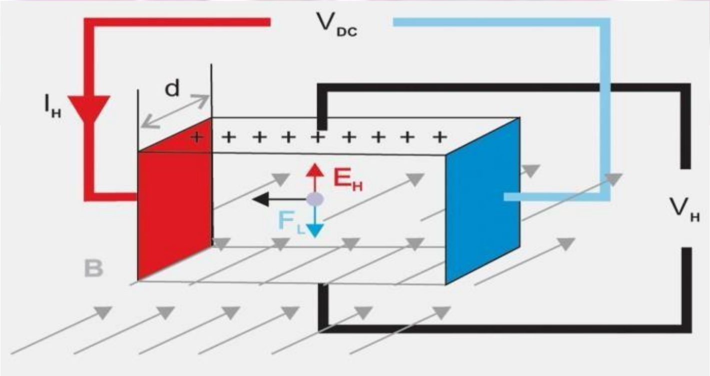
$$J_n(diffusion) + J_n(drift) = 0$$

$$J_p(diffusion) + J_p(drift) = 0$$

## **HALL EFFECT:**

Suppose a material carrying an electric current is placed in a magnetic field. Then an electric field is produced inside the material in a direction which is at right angles to both the current and the magnetic field. This effect was discovered by Edwin H Hall in the year 1879. This phenomenon is known as the Hall Effect and the generated voltage is known as hall voltage.

Let us consider a n-type semiconductor. Let v be the velocity of the electron flowing right to left just opposite to the conventional flow of current and magnetic field is applied perpendicular to the flow of current. Then, the electron experiences a force of 'Bev' due to magnetic field which is perpendicular to both 'B' and flow of current.



Thus electron is deflected causing a negative charge to accumulate on one face of the slab. A potential difference is therefore established between faces and gives rise to a force e$E_H$ on electron in opposite direction. At equilibrium,

$$eE_H = \mathrm{B}e\vartheta$$

$$E_H = \mathrm{B}\vartheta$$

If J is current density, then

$$J = ne\vartheta$$

$$\vartheta = \frac{J}{ne}$$

Therefore,

$$E_H = \mathrm{B}\frac{J}{ne}$$

$$E_H = \mathrm{BJ}R_H$$

Where, $R_H = \frac{1}{ne}$ is called hall coefficient. Since all quantities $E_H$, J, B are measurable, the hall coefficient $R_H$ and hence the carrier density 'n' can be found out.

For, n-type field is developed in negative direction compared to p-type. Therefore,

For n-type, $R_H = -\frac{1}{ne}$

For p-type, $R_H = \frac{1}{pe}$

**Determination of Hall Cooefficient:**

If 'b' is width of sample across which hall voltage $V_H$ is measured. Then

$$E_H = \frac{V_H}{b}$$

$$R_H = \frac{E_H}{BJ}$$

$$R_H = \frac{V_H}{BbJ}$$

$$V_H = R_H\, BbJ$$

If't' is thickness of sample, then current density, $J = \frac{I}{A} = \frac{I}{bt}$

$$V_H = R_H\, Bb \times \frac{I}{bt}$$

$$R_H = \frac{V_H t}{BI}$$

**Determination of Mobility**:

For n-type material, $\sigma_n = ne\mu_e$

$$\mu_e = \frac{\sigma_n}{-1/R_H}$$

For p-type material, $\mu_h = \frac{\sigma_p}{1/R_H}$

**Applications of Hall Effect:**

- Determination of mobility, $\mu = \frac{\sigma}{1/R_H} = \sigma R_H$
- Determination of carrier concentration, $n = \frac{1}{eR_H}$
- Determination of magnetic flux density, $B = \frac{V_H t}{IR_H}$
- Determination of type of semiconductors
  For n-type semiconductor $R_H$ is negative.
  For p-type semiconductor $R_H$ is positive.

## P-N JUNCTION:

### Fabrication:-

When a layer of p-type semiconductor material is placed on the layer of n-type semiconductor material insuch a way that the atoms of p-type combine with the atoms of n-type across the surface contact. Such a surface junction where combination has occurred is known as P-N junction. In practice, a PN junction is obtained in three ways.

1. Grown junction type

2. Fused or alloyed junction type
3. Diffused junction type

**Grown junction type:**

Grown junctions are formed when donor impurities are introduced into one side and acceptor impurities in to the other side of a single crystal at the time of crystal growing from a melt of silicon or germanium.

First germanium or silicon are melt is doped with a small amount of p-type impurity. Then after sufficient time during the growth process an n-type impurity is added in sufficient quantity to overcome the effect of p-type impurity so that subsequently n type material is formed.

Advantages: locating the junction and also attaching leads to narrow grown junction regions is difficult.

**Alloy junction type:**

In this type, p-type and n-type materials are kept in contact and fused together properly by heat treatment to form junction.

Eg: an indium is pressed on a wafer of n-type germanium. During few minutes of heat treatment, indium atom’s fuse into the surface of germanium and produce p-type region. Hence, P-N junction is formed.

**Diffused junction type:**

In this process, a p-type impurity is painted into n-type substrate and both are heated. Now impurity atoms diffuse into n-type substrate for a short distance and from p-n junction.

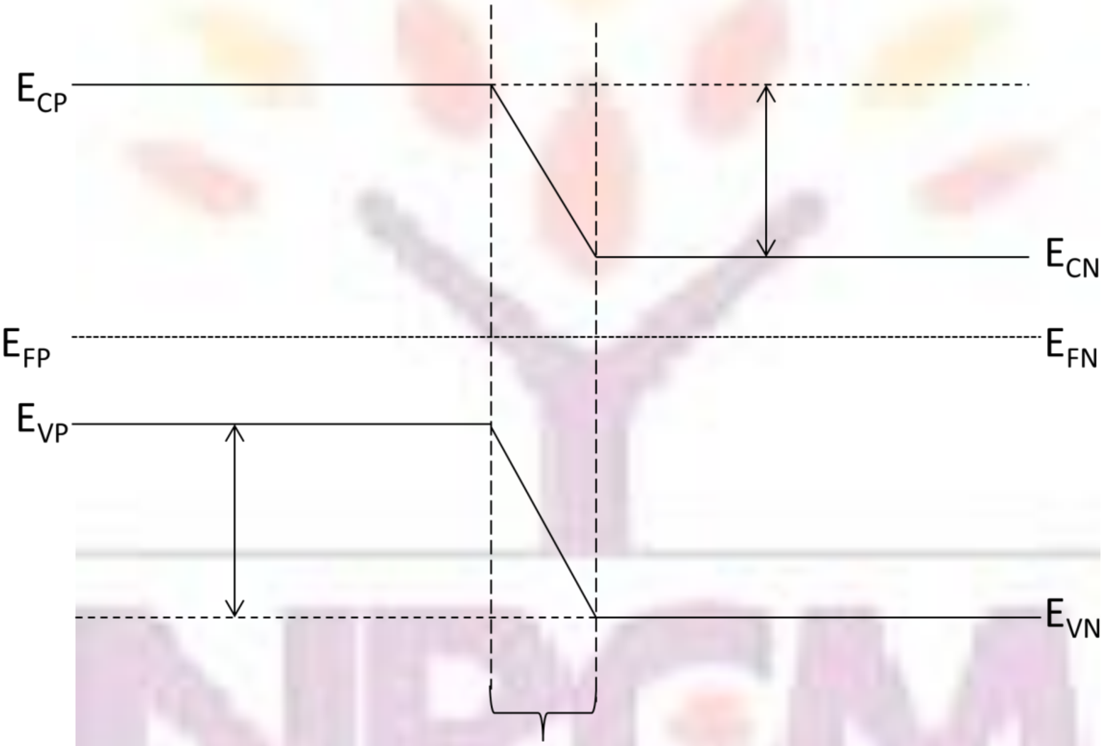
The formation of p-n junction is shown below. When the p-type and n-type are joined, in the region of contact the free electrons diffuse from n-region and combine with holes in p-region. This leaves n-region near the boundary positively charged and p-region negatively.

As a result, electric field $E_B$ appears in small region w on either side of junction. This region is called depletion region. Due to this electric field $E_B$ , potential difference appears across the region and this potential $V_B$ is called contact potential or barrier potential or junction barrier.

## ENERGY DIAGRAM OF PN DIODE:

The energy level diagrams of p-type and n-type materials are as follows.

When PN junction is formed the Fermi levels become common for both the types.



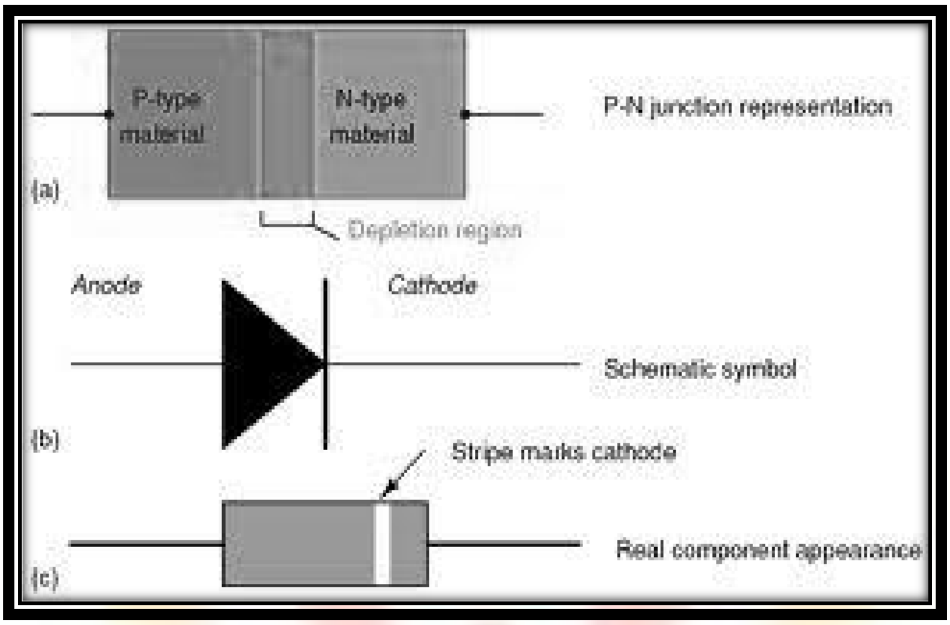
The contact potential $V_B$ across the junction is due to the potentials of depletion regions on n-side $V_n$ and p-side $V_p$ is

$$V_B = V_n - V_p$$

Under unbiased condition, no net current flow at equilibrium. The electric field $E_B$ across the junction is given by

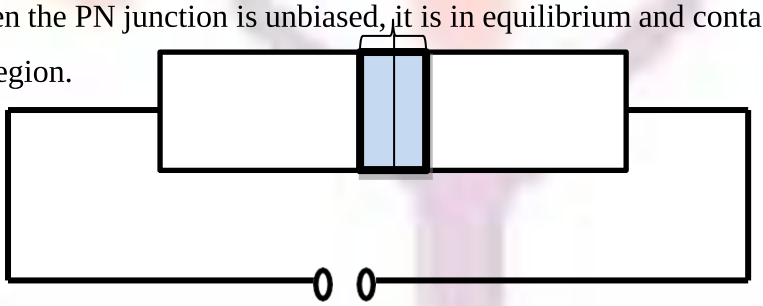
$$E_B = E_{vp} - E_{vn} = E_{cp} - E_{cn} = eV_B = e(V_n - V_p)$$

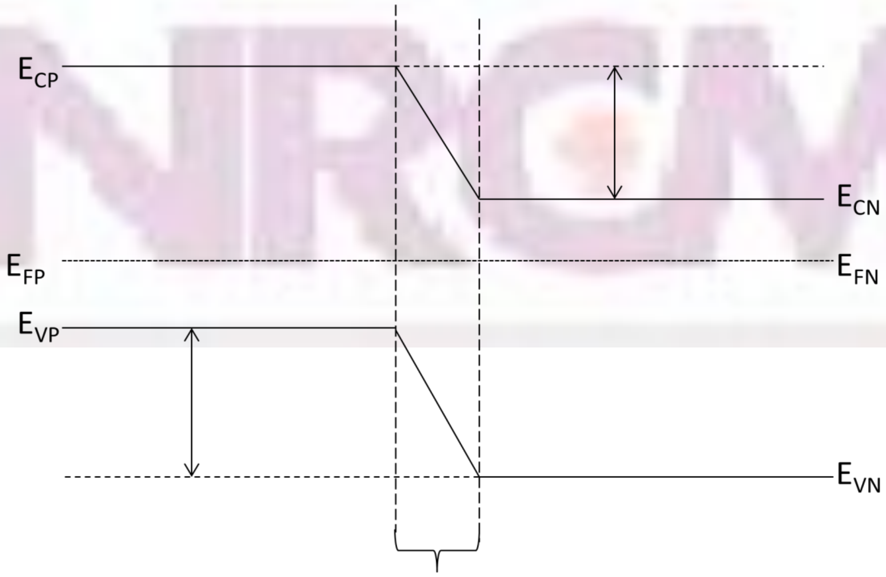
### Symbol of PN junction diode:



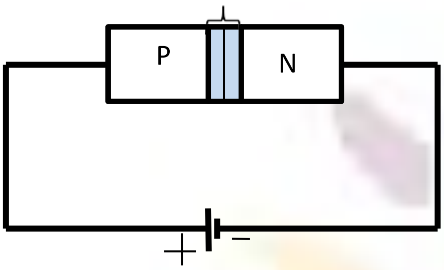
### BIASING OF PN JUNCTION:

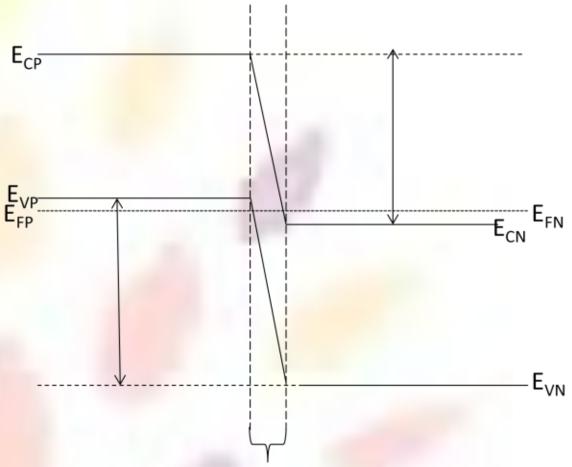
When the PN junction is unbiased, it is in equilibrium and contact potential $V_B$appears across the region.



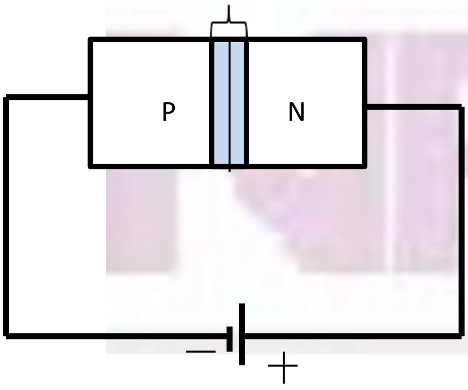


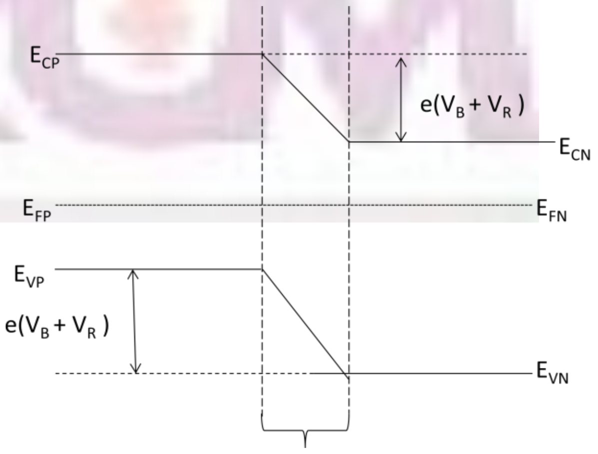
When the positive of the source is connected to the p-side and negative of the source is connected to the n-side, then the junction is said to be forward biased. This voltage appears across the depletion region. Since, $V_B$ acts from n to p, the electrostatic potential barrier is lowered and is given by $V_B - V_f$. The electric field in the transition region reduces. Since, the width of the transition region is proportional to the $\sqrt{V}$, the width of transition region decreases.





When the positive of the source is connected to the n-side and negative of the source is connected to the p-side, then the junction is said to be reverse biased. Since this potential acts along $V_B$, the electrostatic potential barrier increases by $V_B + V_r$ . The electric field in the transition region increases. Since the width of the transition region is proportional to the square root of the electrostatic potential barrier, the width of the transition region increases.





## V-I Characteritics of P-N Junction

### Unbiased Circuit:

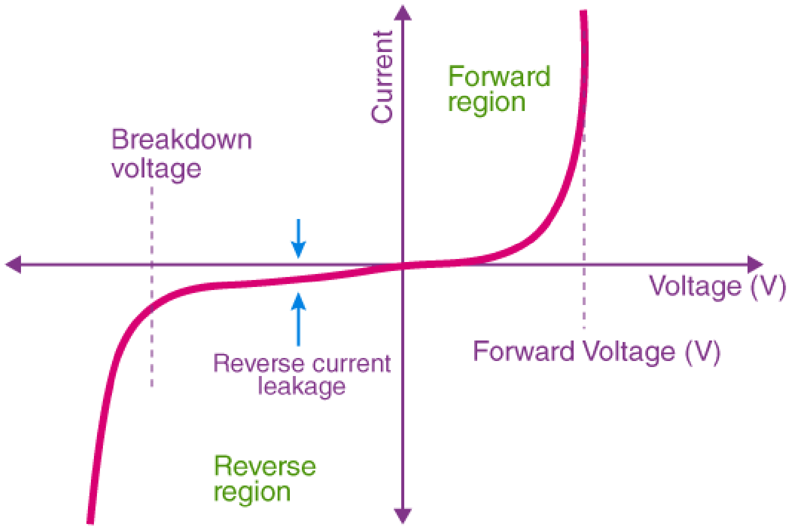
when the junction is not connected to any voltage source, it is said to be unbiased and due to barrier potential across the junction, there is no flow of charge carriers and hence no current flow through the junction.

### Forward biased circuit:

when the diode is forward biased, since the potential barrier height is very small, when the applied voltage exceeds that value, the junction resistance becomes almost zero. Hence, for small increase of applied voltage, large increase in circuit current is observed. The current is called forward current. Under forward bias, the d.c resistance is around 100 ohms for germanium diode.

### Reverse biased circuit:-

When the diode is reverse biased, a slight reverse current (in μA) flows in the circuit. Even for a large increase in bias voltage, there is a negligible increase in current. When the applied reverse voltage is high enough to break the covalent bonds of the crystal, the current rises suddenly. This voltage is called breakdown voltage or reverse voltage. For Ge diode reverse resistance is around 1MΩ.



# UNIT-3

# PHYSICS OF SEMICONDUCTOR DEVICES

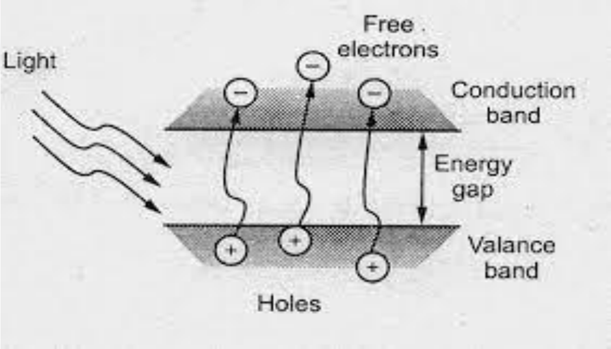
## INTRODUCTION:

Conductivity of silicon is about $10^{11}$ times lesser than that of copper and is about $10^{13}$ times higher than that of fused quartz.

- And also conductivity of semiconductors increases as the temperature is increased
- Devices made of semiconductors are small with less weight, more reliable and inexpensive.
- The vacuum tubes have been replaced by semiconductor devices like p-n junction diodes, transistors etc.
- The advantages of semiconductors over vacuum tubes are
  - Vacuum tubes require vacuum, but semiconductor devices doesn’t need.
  - Semiconductor devices are smaller in size, lighter in weight.
  - Semiconductor devices are operated at very low voltages.
  - Power consumption is also very low for semiconductor devices.
  - Performance of semiconductor devices is very reliable than vacuum tubes.
  - Operating life of semiconductor device is appreciably longer than vacuum tube.
- Silicon has almost no free electron at room temperature as compared with ‘Ge’ .hence ‘Si’ is preferably used in fabrication of semiconductor devices.

## CARRIER GENERATION:

Carrier generation is a process where electron-hole pairs are created by exciting an electron from the valence band of the semiconductor to the conduction band, there by creating a hole in valence band.



## RECOMBINATION OF CARRIERS:

Any electron which exists in the conduction band is in a meta-stable state and will eventually fall back to a lower energy position in the valence band filling a hole in the valence band.Due to de-excitation of electrons to lower levels there by producing or emitting extra energy in the form of radiations. There are two types recombination’s.

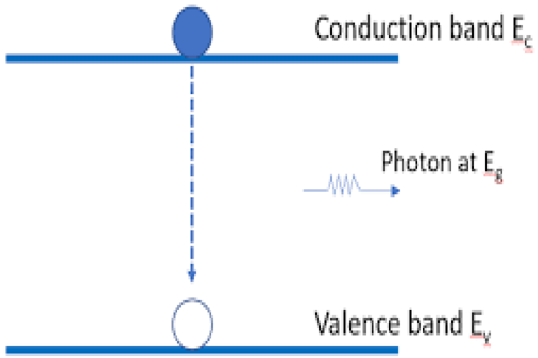
- Radiative recombination
- Non radiative recombination.

Again non radiative recombination is of two types

- Auger recombination and
- Trap assisted recombination

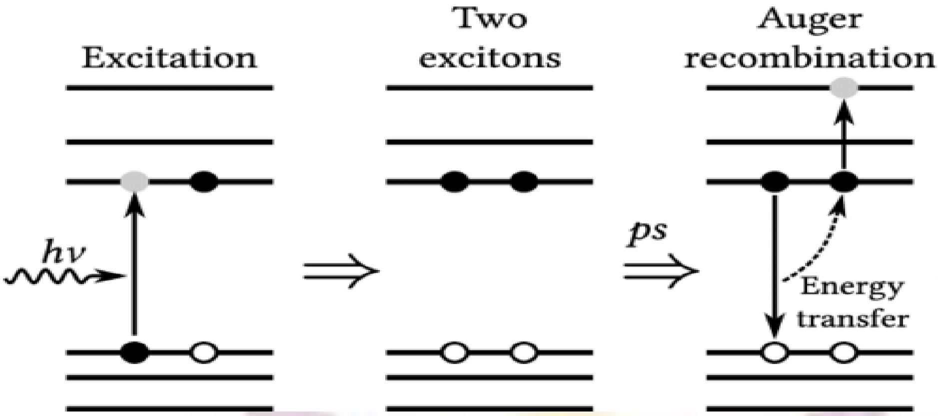
## Radioative recombination:

It is the recombination mechanism that dominates in direct band gap semiconductors.A direct band gap semiconductors is one in which the maximum energy level of valence band aligns with the minimum energy of the conduction band. In this process when the electron moves from its conduction band in to the empty valence band state associated with a the energy is released in the form of radiations. Depending on the material chosen, the out put radiation will be either light or heat energy.



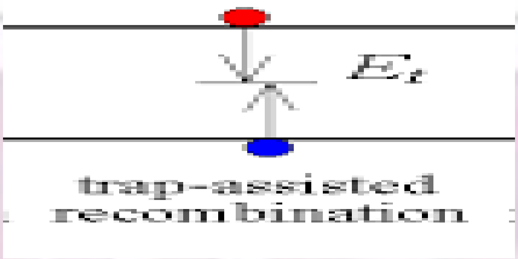
## Auger recombination:

An auger recombination involves three carriers.An electron and a hole recombine, but rather than emitting the energy as heat or a photon, the Energy is given to a third carrier, an electron in the conduction band.This electron then thermalises to conduction band. Auger recombination is most important in heavily doped material.



**Trap-assisted recombination:**

This recombination is otherwise called as shockley-readhall recombination.This recombination is called as trap assisted because th deexcited electron from higher energy level falls into trap.The trap is an energy level within the band gap caused by the presence of foreign atom or structural defects.The electron occupying the trap, in a second step, moves into an empty valence band state thereby completing the recombination process.



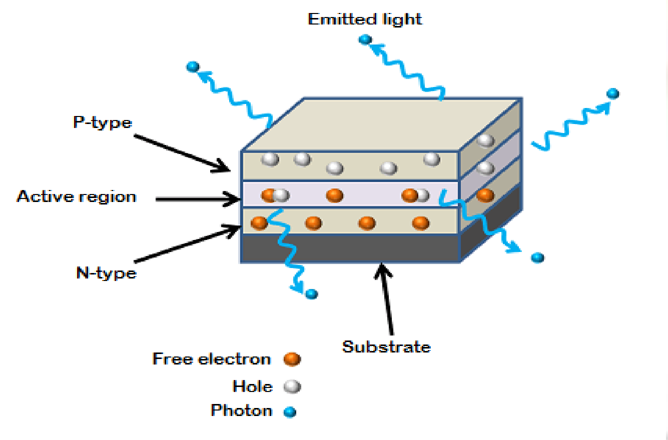
## LIGHT EMITTING DIODE:[LED]

**Construction:-** the typical construction of LED is as shown in figure.

LED has to be constructed in such a way that most of the radiative recombination's takes place from the side of the junction nearest to the surface so that loss due to reabsorption is minimised.

The LED is constructed on a GaP n-doped substrate. A thin epitaxial p-doped GaP layer is grown on the top of this substrate.

Electrical contacts can be made leaving as much of the upper surface of the p-type material uncovered. The recombination takes place and radiation is generated between p and n layers i.e., PN junction. Since GaP layer is transparent, the radiation escapes through the top layer. To the bottom electrode a reflective layer is added to improve efficiency.



**Requirements:-**

LED material must have energy gap of appropriate width, both p and n types must exist with low resistivity's, efficient radiative paths must be present.

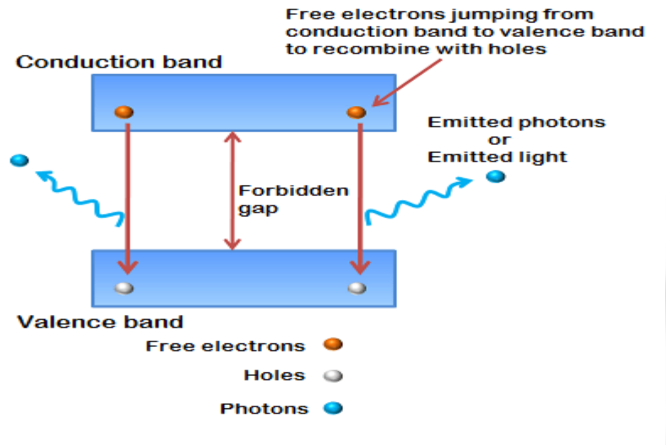
**Working:-**

PN junction diode operated under forward bias gives rise to injection luminescence.

Under forward bias, majority carriers from both sides of the junction cross the internal potential barrier and enter the other side of the junction. Where they are minority charge carriers. This process is called minority carrier injection.

These excess minority carriers while diffusing away from the junction undergo radiative recombination with majority carriers, emitting photons.

The no. of radiative recombination’s is proportional to the carrier injection rate.



Process of light emission in LED

**Advantages:-**

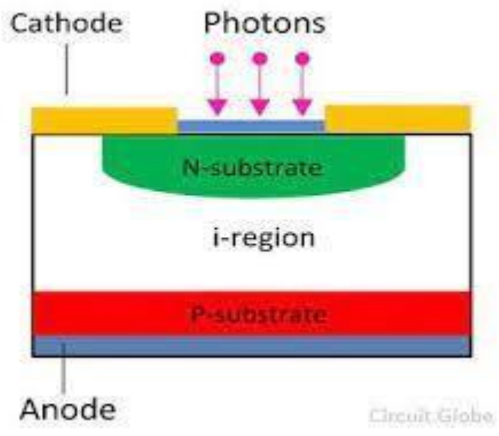
- o/p is bright
- they can be operated in a wide range of temperature 0 to 70
- Available in different colours.
- Very small in size
- Has long life and high degree of reliability
- Viewing angle is not limited.

## PHOTO DIODE:-

**Construction:** the typical silicon photodiode structure for photo-conductive operation is as shown below.

A junction is formed between heavily doped p-type material ($P^+$) and fairly lightly doped n-type material so that the depletion region extends well in to the n-material.

Metallic contacts can be made directly to the $P^+$ material but to obtain an ohmic contact to the n- material an intermediate $n^+$ layer is formed.



**Working:-** the function of the photodiode junction is the opposite of an LED junction.

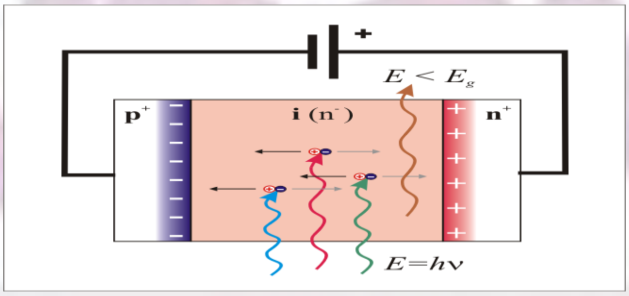
In a PN junction diode, the depletion region is formed on the either side of the junction when there are no free carriers.

Only ionised atoms of opposite polarity remain. When an electron-hole pair is generated by photon absorption within this region, the internal fields causes the electron and hole to separate.

This charge separation can be detected in two different methods.

If the device is left on open circuit an externally measurable potential appears between p and n regions. This is known as photo voltaic mode of operation.

If we short circuit the device externally, the external current flows between the p and n regions. This is known as photo conductive mode of operation.



**Characteristics:**

The amount of photo current generated is independent on the amount of incident optical power. As more photons are incident on th active region, more charge carriers are created, hence more photo current.

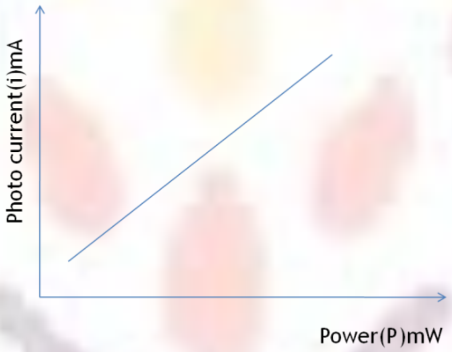
I=s.P

Where, I-photo current

s- responsivity of photo diode

P- optical power.

At high incident light intensity, photo diode is saturated due to depletion of carriers. Thus, excess photons are not absorbed.



**Advantages:**

1. Low noise
2. Low dark current
3. Low bias voltage
4. Higher reverse voltages to be tolerated
5. High-speed response
6. Low junction capacitance
7. Large depletion region

**Disadvantages of PIN diode :**

1. Less sensitivity.
2. No internal gain.
3. Small area.
4. Slow response time.
5. High reverse recovery time due to power loss are significant.

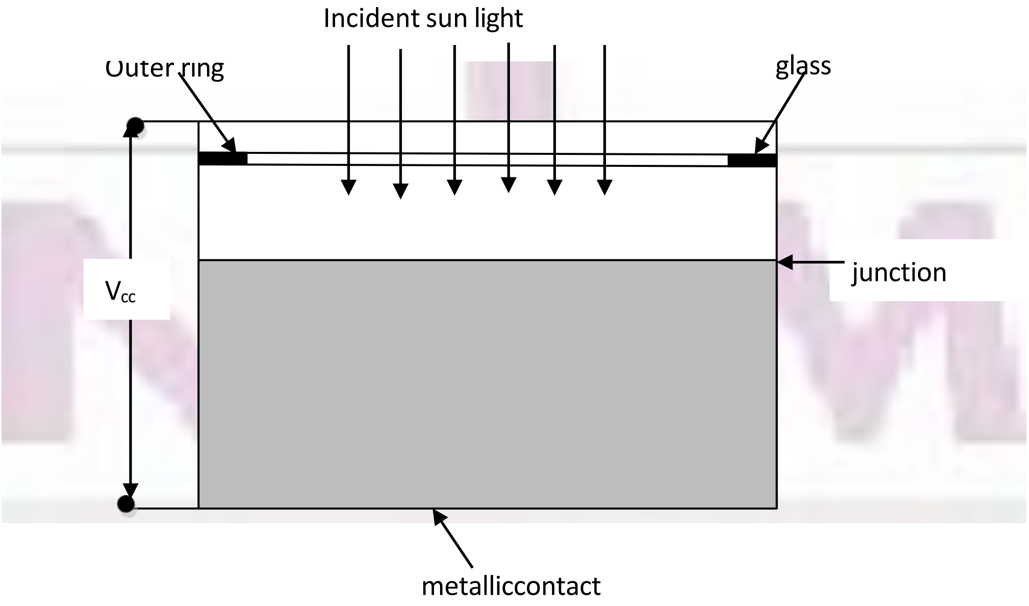
**Applications:**

1. These diodes are used in the RF and also for microwave switches and microwave variable attenuators since they are said to have low capacitance.
2. They are used in Photodetectors and photovoltaic cell and the PIN photodiodes are used for fibre optic network cards and also switches.
3. These diodes are effectively used for RF protection circuits and it can also be utilized as an RF switch.
4. The PIN photodiode is also used to detect X-rays and gamma rays photons.

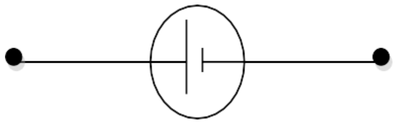
## SOLAR CELL:

The solar cells are semiuconductor junction devices which are used for converting optical radiation in to electrical energy. The generated electric voltage is proportional to the intensity of incident light. Due to their capability of generating voltage, they are called as photovoltaic cells. A solar cell converts photon power into electric power and delivers this power to load.

**Construction:** figure shows the construction of solar cell.



**Symbol:** the circuit symbol for solar cell is



The cell is a P- N junction diode with appropriately doped semiconductors. The top p-type layer is made very thin so that the light radiation may penetrate to fall on junction. The doping level of p-doped semiconductor is very high. Every effort is made to ensure that the surface area perpendicular to sun is maximum. P- Type material is surrounded by a nickel plated ring which serves as the positive terminal of the cell. A metallic contact at the bottom of the cell acts as a negative terminal.

**Working:** when a photon of light energy collides with the valence electron either in p-type or n-type material, it imparts sufficient energy to the electron to leave its parent atoms. As a result, free electrons and holes are generated on each side of the junction.

In p-type material, the newly generated electrons are minority carriers which are free to move across the junction with no applied bias. In n-type material, the newly generated holes are minority carriers which are free to move across the junction with no applied bias. The result is an increase in minority carriers flow. In this way depletion region potential causes the photo current to flow through the external load.

**Advantages:**

1. It is a self generating device.
2. Pollution free energy conservation system.
3. It can be operated over a wide range of temperatures
4. These are extensively used in space satellites for long period of time for source of power.

**Limitations:**

1. Low efficiency
2. Doesn’t convert all solar rays in to electrical energy.
3. More effective in outer space applications than terrestrial applications.

**Applications:**

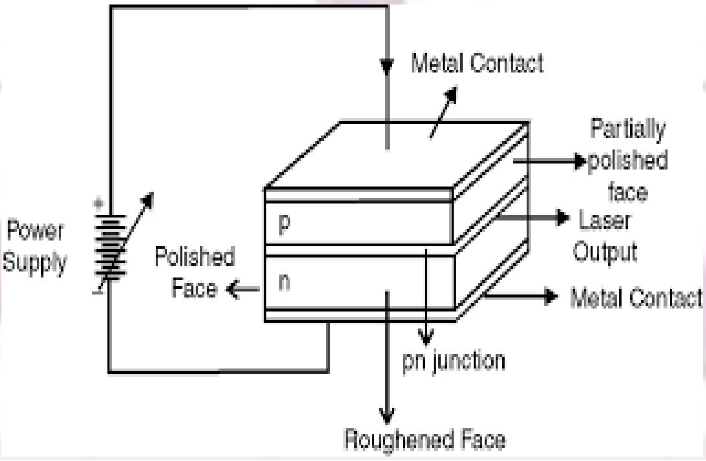
1. In portable exposure meters
2. In space satellites
3. In low resistance relays for ON and OFF operations.
4. Used in detectors.

## SEMICONDUCTOR LASER DIODE:

The semiconductor laser is also called as diode laser. It has very important application in fibre optic communication. The wave length of the emitted light depends up on the band gap of the material. If p and n-type materials are prepared from the same material then the p-n junction is called as homojunction semiconductor laser source. If p and n type materials are prepared from different materials then they are called as hetro junction semiconductor laser source.

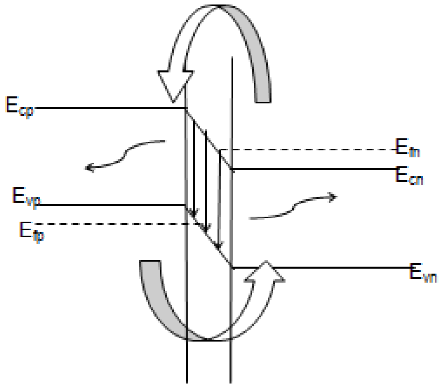
**Principle**:When a p-n junction diode is forward biased, at junction holes and electrons recombination occurs. Due to recombination photon are emitted. This emitted photons stimulate further recombination and hence a laser output is obtained.

**Construction:** GaAs crystal which is heavily doped with suitable dopants to form a p-n junction.At the junction the sides through which emitted light is coming out are well polished and parallel to each other.Two metal contacts are taken , one from the p-type and other from the n-type which acts like a cathode and a anode.Since the p and n-type materials are prepared from the same material,the p-n junction is called as homojunction semiconductor laser source. The basic mechanism responsible for light emission from a semiconductor is the recombination of electrons and holes at p-n junction when a current is passed through the diode.



**Working:** When a current is passed through a p-n junction, holes are injected from p-region into n-region and electrons are injected from n-region into p-region as junction is forward biased. The electrons are minority charge carriers in p-side and holes are minority charge carriers in n-side.The excess minority charge carriers recombine with majority charge carriers of n and p material, resulting in the release of photons. Further emitted photons increase the recombination rate. Only pulsed output is obtained. This drawback is overcome in hetro junction laser structure. For example Ga Al As.

## ENERGY LEVEL DIAGRAM:



**Characteristics:**

The characteristics are drawn between output current and output light intensity. Below the threshold current, the output is due to minority charge carrier recombination. Further emitted photons increase the recombination rate, current increases sharply after the threshold current, hence the light output also.

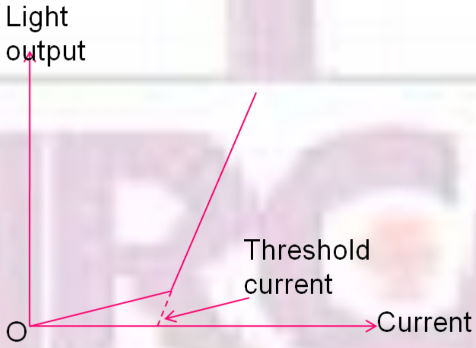


**Figure of merits:**

1. Semiconductor lasers are cheapest and smallest lasers available
2. Semiconductor lasers are Massey produced and easily fabricated
3. The laser output can be easily modulated
4. Highly efficient

**Disadvantages:**

1. It is very difficult to grow different layers of PN junction.
2. The cost is very high.

**Applications of laser diode:**

1. Fibre optic communication
2. Metal cutting
3. Welding
4. Lasers are widely used in electronic industry in trimming the components of ICs.
5. Lasers are used to destroy kidney stones and gall stones. The laser pulses break the stones into small pieces.
6. Lasers are used in cancer diagnosis and therapy.
7. Lasers are used in blood loss less surgery

# UNIT-4

# LASERS & FIBER OPTICS

## INTRODUCTION:

The light emitted from a conventional light source said to be incoherent because the radiation emitted from different atoms do not bear any definite phase relationship with each other.

LASER-light amplification by stimulated emission of radiation.

LASER is also a light source having high monochromacity, high intensity, high directionality and high degree of coherence. Lasing has been extended up to $\gamma$ $-$rays. $\gamma$ $-$Ray Lasers are called as Grasers. The Laser is the outgrowth of Maser which means microwave amplification by stimulated emission of radiation. If the stimulated radiation lies in optical region, then the device is called as optical MASER or LASER.

## CHARACTERISTICS OF LASER:

The important characteristics of a LASER radiation are

1. Laser is highly monochromatic
2. Highly directional
3. Highly coherent
4. Highly intensified

**Monochromatic:** The Laser light is highly monochromatic. The spread is of the order of few angstroms only. That is less than 10A. and Laser emit continuous waves of very long duration.

**Directional:** The emitted lights from LASER are only in one direction as the photons travelling along the optical axis of the system.

**Coherent:** the waves emitted by a laser source will be in phase and are of same frequency. Whereas convention light source [incandescent lamp] emits random wavelength light waves with no common phase relationship.

**Intensity:** a LASER beam emits light in the form of a narrow beam which propagates in the form of plane waves. As the energy is concentrated in a very narrow region, its intensity is tremendously high. It is estimated that light from a typical 1mW LASER is 10000 times brighter than the light from the source at the earth's surface.

**Divergence:** the divergence or angular speed of the LASER beam is extremely small. The angular speed is given by

$$\Delta\theta = \frac{1.22\lambda}{d}$$

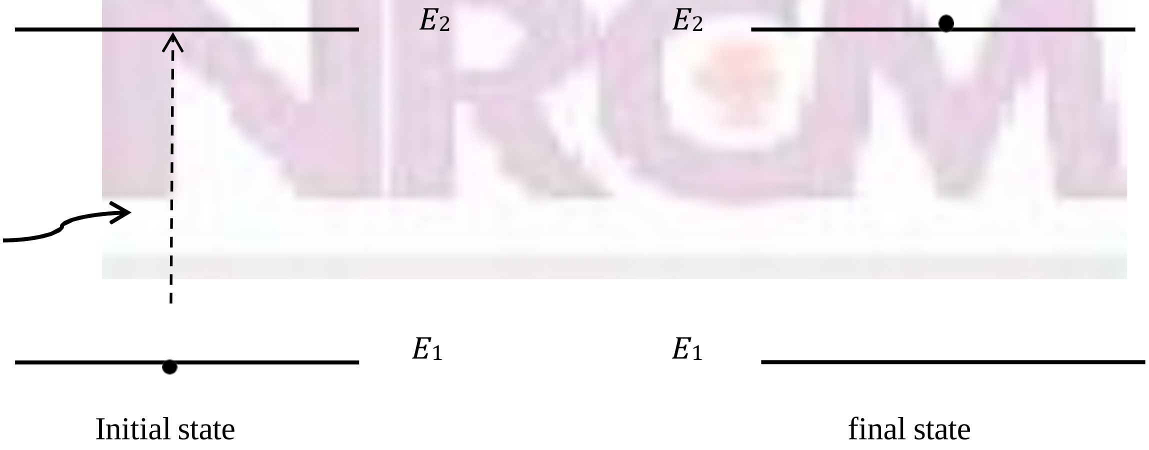
Where 'd' is diameter of the front mirror. In case of gas lasers $\Delta\theta$ is small as $10^{-5}$ to $10^{-6}$ radians.

## SPONTANEOUS AND STIMULATED EMISSION OF RADIATION:

Consider a radiation interacts with matter. for interaction to occur, first of all the energy of the interacting photon $h\vartheta$ must match with energy difference between the two states of the atoms involved in the interaction.

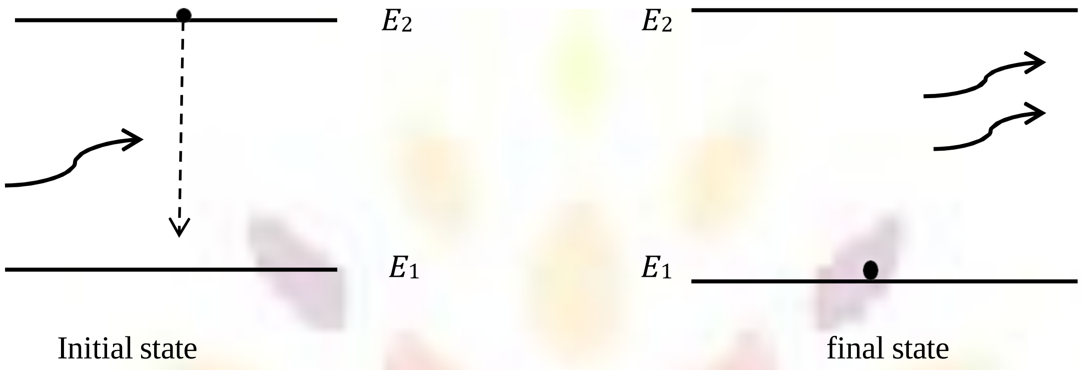
### Stimulated absorption:

If the radiation interacts with atoms in the lower energy state say $E_1$, the atoms absorb the energy and get excited to higher energy state $E_2$. This process is called stimulated absorption.



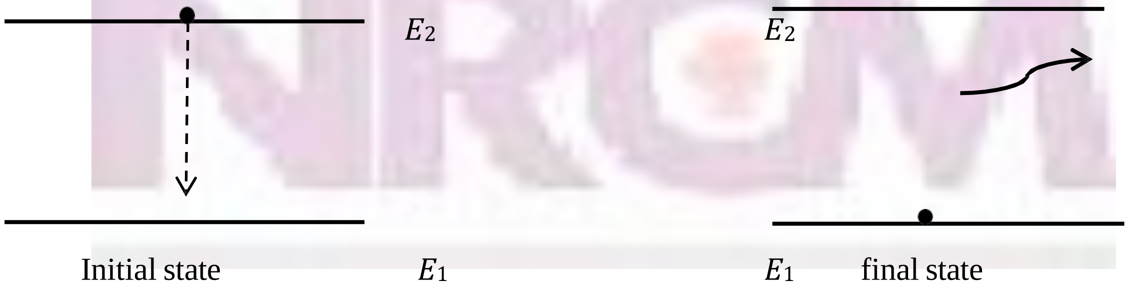
Stimulated emission:

If the radiation interacts with atoms which are already in the exictedstate $E_2$, then the atom comes to the lower energy state $E_1$ occurs with the emission of photons of energy $h\vartheta$. This process is called stimulated emission.



Spontaneous emission:

In this process, the atoms in the exited state drop to the lower energy state after they have stayed in excited state for some time called life time. During this process, photon of energy $h\vartheta$ has been emitted. The life time of the particle in the excited state is of the order $10^{-8}$ sec. There exist some excited states in which life time is much greater than $10^{-8}$ sec. these states are called metastable states. The life time of the atom in meta stable state is of the order $10^{-3}$sec.



## EINSTEIN COEFFICIENTS AND THEIR RELATIONS:

Consider a substance, in which the process of stimulated absorption, spontaneous emission and stimulated emission occur simultaneously. Let $N_1$ be the no. of atoms per unit volume with energy $E_1$ and $N_2$ be the no. of atoms per unit volume with energy $E_2$. Let 'n' be the no. of photons per unit volume with a frequency $\vartheta$ such that $h\vartheta = E_2 - E_1$. Then, energy density of interacting photon is given by

$$\rho(\vartheta) = nh\vartheta \text{......................}(1)$$

Stimulated absorption rate depends on the no. of atoms available in $E_1$ as well as the energy density interacting radiation. Therefore, stimulated absorption rate is

$$\propto N_1$$

$$\propto \rho(\vartheta)$$

$$= \rho(\vartheta)N_1B_{12} \dots\dots\dots\dots (2)$$

Where $B_{12}$ is Einstein coefficient of stimulated absorption.

Once they are excited to higher states, after their life time they move to their lower energy level spontaneously emitting photons. This spontaneous emission rate depends on the no. of atoms in the excited energy state. Therefore, spontaneous emission rate is

$$\propto N_2$$

$$= N_2A_{21} \dots\dots\dots\dots (3)$$

Where$A_{21}$ is Einstein coefficient of spontaneous emission.

Before de-excitation to lower energy level, they may interact with photons resulting in stimulated emission of photon. That stimulated emission rate depends on

$$\propto N_2$$

$$\propto \rho(\vartheta)$$

$$= \rho(\vartheta)N_2B_{21} \dots\dots\dots\dots (4)$$

Where $B_{21}$ is Einstein coefficient of stimulated emission.

At equilibrium, the upward transition rate must be equal to downward transition rate.

$$\rho(\vartheta)N_1B_{12} = \rho(\vartheta)N_2B_{21} + N_2A_{21}$$

$$\rho(\vartheta) = \frac{A_{21}N_2}{N_1B_{12} - N_2B_{21}}$$

$$\rho(\vartheta) = \frac{A_{21}/B_{21}}{\frac{N_1\,B_{12}}{N_2\,B_{21}} - 1} \dots\dots\dots..(5)$$

According to Maxwell Boltzmann statistics, the population of various levels is

$$N_i = N_0 g_i \exp\frac{-E_i}{KT} \dots\dots (6)$$

Hence,

$$N_1 = N_0g_1 \exp\frac{-E_1}{KT}$$

$$N_2 = N_0g_2 \exp\frac{-E_2}{KT}$$

$$\frac{N_1}{N_2} = \frac{g_1}{g_2}\exp\frac{E_2 - E_1}{KT} \dots\dots (7)$$

Substituting (7) in (5)

$$\rho(\vartheta) = \frac{A_{21}/B_{21}}{(\frac{g_1\,B_{12}}{g_2\,B_{21}}\exp\frac{E_2-E_1}{KT}) - 1} \dots\dots..(8)$$

From Planks law of black body radiation, the radiation density

$$\rho(\vartheta) = \frac{8\pi h\,\vartheta^3/c^3}{exp\,(\frac{E}{KT}) - 1} \dots\dots\dots\dots(9)$$

Comparing equations (8) & (9)

$$\frac{g_1}{g_2} = \frac{B_{12}}{B_{21}} = 1 \dots\dots\dots.(10)$$

And $A_{21}/B_{21} = 8\pi h\, \vartheta^3/c^3 \ldots\ldots\ldots..(11)$

Equations (10) & (11) are called as Einstein relations.

Case-1:

The ratio of spontaneous emission rate to the stimulated emission rate is given by

$$R = \frac{N_2 A_{21}}{N_2 B_{21}\rho(\vartheta)} = \frac{A_{21}}{B_{21}\rho(\vartheta)} = exp\,(\frac{h\vartheta}{KT}) - 1$$

Therefore, spontaneous emission rate predominates. To make R smaller, $\rho(\vartheta)$ has to be made large.

Case-2:

The ratio of stimulated emission rate to the stimulated absorption rate is given by

$$Q = \frac{N_2 B_{21}\rho(\vartheta)}{\rho(\vartheta) N_1 B_{12}} = \frac{N_2}{N_1}$$

At thermal equilibrium, $\frac{N2}{N_1} \ll 1$

Instead of this, if we create $N_2 > N_1$, stimulated emission will predominant. If stimulated emission predominates the photon density increases and LASER occur.

To achieve more stimulated emission, population of excited state ($N_2$) should be made larger than the population of the lower state ($N_1$). This condition is called population inversion.

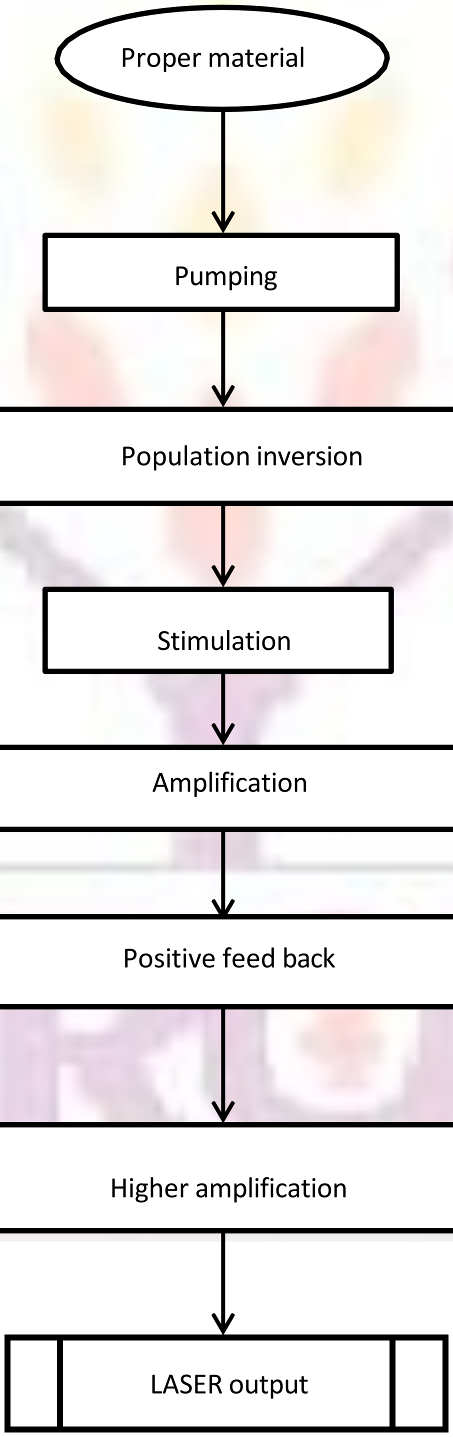
To have LASER,

- Create population inversion.
- Increase the energy density of interacting radiation.

## LASER ACTION:

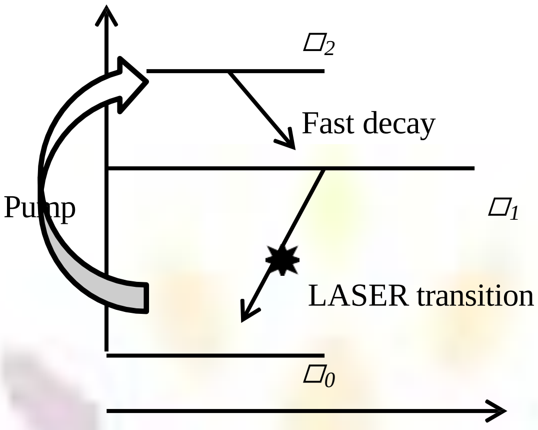
Using pumping process, the no. of atoms in the excited state ($N_2$) is greater than the no.of atoms in the ground state ($N_1$). i.e., $N_2 > N_1$. It is called as population inversion state.

In the presence of external photon, we can induce the atoms in the excited state to undergo transition to lower energy state. This is the process of stimulated emission. The avalanche effect takes place and hence there is an amplification of light. By resonator cavity proper feedback is given and there is enormous amplification. The output is LASER radiation.



## POPULATION INVERSION:

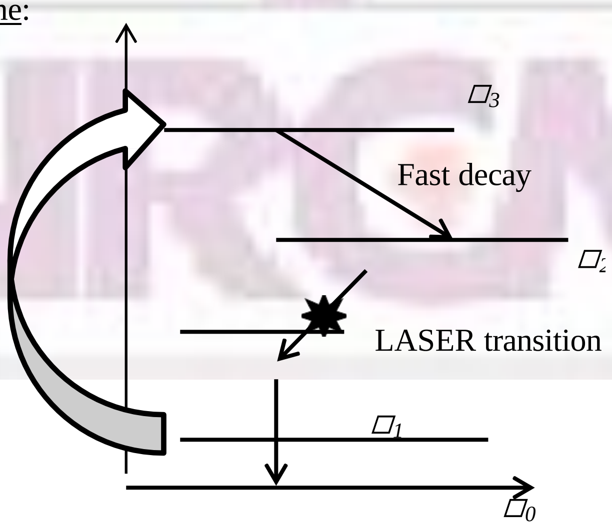
Three level scheme:



If the collection of atoms is intensely pumped, a large no. of atoms are excited through stimulated absorption to the highest energy level $\square_2$. If the level $\square_2$ has very short life time, the atoms decay fast to level $\square_1$. If the level $\square_1$ has relatively longer life time [a state known as metastable state] atoms tend to accumulate at $\square_1$. With intense pumping, $\square_1$ is more populated than $\square_0$. And LASER transition takes place between level $\square_1$ and level $\square_0$.

Hence population inversion is achieved between $\square_1$ and $\square_0$. If the pumping continues when the condition $\square_1 > \square_0$ is reached, stimulated emission rate exceeds stimulated absorption rate. This scheme can be worked in pulsed mode only. For example ruby laser.

Four level scheme:



On pumping, the atoms are lifted from the ground state to the highest of the four levels involved in the process. From this level, the atoms decay to the metastable state $\square_2$, and the population of this state grows rapidly. Hence, population inversion exist between $\square_2$and$\square_1$. Therefore, laser transition takes place between higher energy level $\square_2$ and lower energy level$\square_1$. Hence, continuous o/p is obtained. For this to happen $\square_1$to $\square_0$ transition should be fast. If this transition ($\square_1 \rightarrow \square_0$) is slow, even four level lasers will work in pulsed mode only.

Eg: He-Ne laser for continuous o/p and $\square_2$ laser for pulsed o/p.

## MECHANISM FOR PUMPING SCHEMES:

There are different mechanisms applied to pump the atoms to higher energy states to create population inversion. They are

- Optical pumping
- Electric discharge
- Chemical reaction
- Injection current

**Optical pumping**: solid lasers are optically pumped using Xenon flash lamps. Since these materials have very broad band absorption, sufficient amount of energy is absorbed from the emission band of flash lamp and population inversion is created. For example Ruby LASER, Nd:YAG, Nd:glass, dye etc.

**Electric discharge**: population inversion can also be achieved by direct excitation as it occurs in an electric discharge. The best example for this method is argon ion laser.

In some lasers one type of atoms are excited by electric discharge. These atoms collide in elastically with another type of atoms. The latter atoms provide population inversion needed for laser emission. The best example is He-Ne laser.

**Chemical reaction:** in this the energy is supplied directly from a chemical reaction not from any other source. For example carbon dioxide laser.

Injection current: in some semiconductors, lasing action is produced by the conversion of electrical energy into light energy in which recombination of electrons and holes occurs. For example gallium arsenide laser.

## ELEMENTS OF LASER:

Active medium: the active medium is a collection of atoms or molecules that can be excited to a state of inverted population. The two states chosen for the lasing transition must possess certain characteristics.

First, atoms must remain in the upper lasing level for a relatively long time to provide more emitted photons by stimulated emission than by spontaneous emission.

Second, there must be an effective method of “pumping” atoms from the highly populated ground state into the upper lasing state in order to increase the population of the higher energy level over the population in the lower energy level.

The active medium may be a gas, a liquid, a solid material or a junction between two slabs of semiconductor materials.

Pumping mechanism: the excitation mechanism is a source of energy that excites, or pumps, the atoms in the active medium from a lower to a higher energy state in order to create a population inversion.

In gas and semiconductor lasers, the excitation mechanism usually consists of an electric current flow through the active medium. Solid and liquid lasers most often employ optical pumps.

Resonant cavity: the feedback mechanism returns a portion of the coherent light originally produced in the active medium back to the active medium for further amplification by stimulated emission

The feedback mechanism usually consists of two mirrors. Each one at end of the active medium aligned in such a way that they reflect the coherent light back and forth through the active medium.

Laser action: when the excitation mechanism of a laser is activated, energy flows in to the active medium, causing atoms to move from the ground state to certain excited state. In this population inversion is created.

Some of the atoms in the upper lasing level spontaneously emitting incoherent photons. When these photons travel along axis of the active medium produce stimulated emission.

## RUBY LASER:

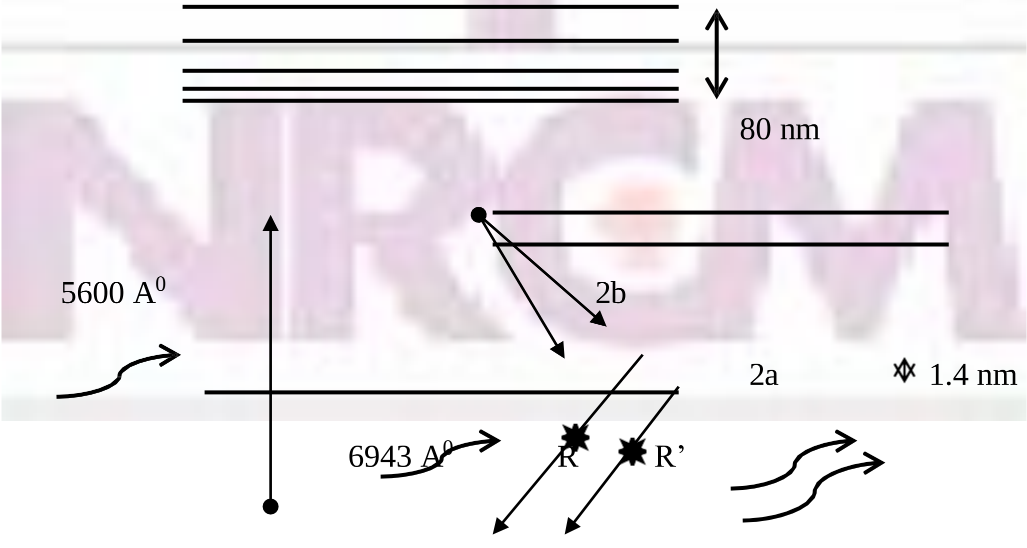
Ruby laser is a three level solid state laser and was constructed by malman in the year 1960. It is a pulsed laser having very high power of hundreds of megawatt in single pulse with about 10 ns duration. Ruby rods are prepared from $□□_2□_3$ doped with 0.05% chromium by weight. So, that some of the $□□^{3+}$ions are replaced by $□□^{3+}$ ions. The ruby laser systems consist of mainly three parts:

Active medium: ruby crystal in the form of a rod of nearly 10 cm in length and 0.8 cm in diameter.

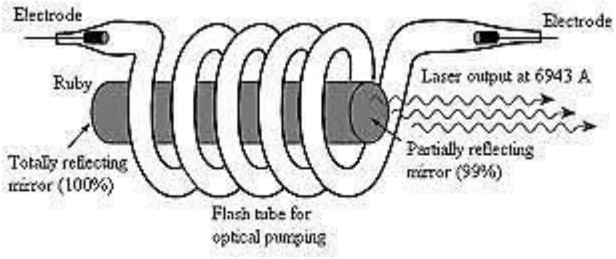
Resonant cavity: flat end faces A and B of the rod are made strictly parallel, plane and silvered so that the end faces A becomes fully reflecting and the end face B partially reflecting. The rod is surrounded by a cylindrical glass tube through which water circulates to keep the rod cool.

Pumping system: the ruby rod is arranged along the axis of a helical xenon flash tube so that the coils of the tube surround the rod. The flash tube is provided with a suitable power supply to flash for several milliseconds.

**Construction:** the ruby rod is surrounded by a xenon flash lamp tube which provides the optical pumping to raise the $□□^{3+}$ ions to upper energy level. The energy level diagram of ruby laser is



Where R=692.7 $A^0$ and R'=694.7 $A^0$.



**Working:** when light from the flash tube is made to fall upon the ruby rod, the chromium atom absorb the green component 560 nm and get excited from level 1 to energy level 3. Chromium ions stay here for a very short time of the order of $10^{-3}$ seconds. The transition from $\square_3$to $\square_2$ is non radiative in nature but produces heat. Hence cooling system is essential. As the life time of $\square_2$ is much longer, the no. of ions in this state goes on increasing while in the ground state goes on decreasing. In this way population inversion exist between $\square_2$and $\square_1$. When an ion passes spontaneously from the metastable state $\square_2$ to the ground state $\square_1$, it emits a photon of wave length 694.3nm. This photon travels through the ruby rod and if it is moving parallel to the axis of the crystal, is reflected back and forth by the silvered ends until it stimulates an excited ion in $\square_2$ and causes it to emit fresh photon in phase with the earlier photon. This stimulated transition triggers the laser transition. The process is repeated again and again and the photons thus get multiplied. When the photon beam become sufficiently intense, such that the part of it energies through the partially silver end of the crystal. O/p is pulsed.

**Applications:**

1. Holography
2. For drilling high quality holes
3. In military as target designators and range finders.

## He-Ne LASER:

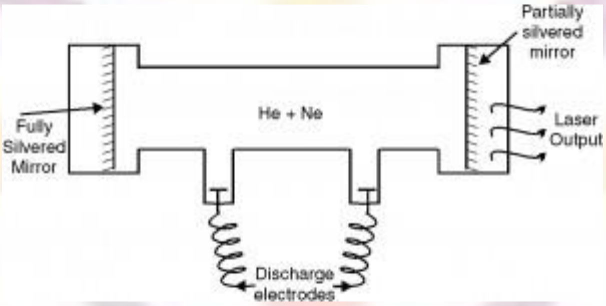
For the continuous laser beam, He-Ne laser is used. The o/p laser is highly mono chromatic, coherent and directional but o/p is generally few mill watts. He-Ne gas lasers are used in holograms and in medicine. The He-Ne laser mainly consists of

Active medium: this laser consists of a gas discharge tube of length 80cm and diameter 1cm. The tube is made up of quartz and is filled with a mixture of neon under pressure of 0.1 mm of Hg and helium under a pressure of 1mm of Hg. The ratio of He-Ne mixture is 10:1.

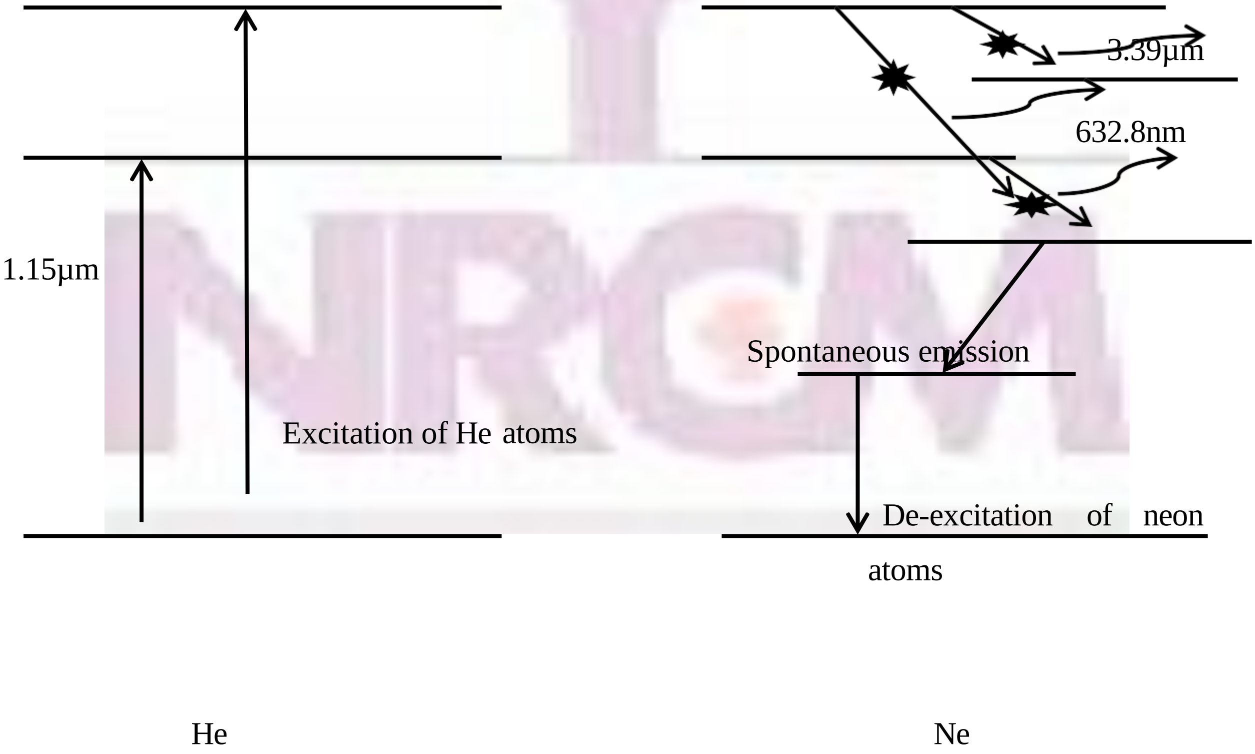
Resonant cavity: the mixture is enclosed between a set parallel mirrors forming a resonating cavity. One of the mirrors is completely reflecting and the other is partially reflecting.

Pumping scheme: the electric discharge is efficient method of producing population inversion in these gas lasers.

Construction: the construction of this laser is as shown below



The different energy levels of helium atoms and neon atoms is



Working:

The levels $E_2$ and $E_3$ of helium have nearly the same energy as the $E'_4$ and $E'_6$ of neon. Where $E_2$ and $E_3$ are metastable states. When discharge is passed through the mixture of gas, the electrons collide with helium atoms and excite them to the metastable states $E_2$and $E_3$. This is called pumping. The He atoms continue in these states in long time.

The He atoms collide with unexcited neon atoms raising them to the levels $E'_4$and$E'_6$. Hence population inversion occurs w.r.t the levels $E'_3$ and $E'_5$. Therefor the transitions occur are

1. $E'_6 \rightarrow E'_5$ producing laser of 3.39 μm
2. $E'_6 \rightarrow E'_3$ producing laser of 632.8nm
3. $E'_4 \rightarrow E'_3$ producing laser of 1.15 μm

From the level $E'_3$ the Ne atoms drop to level $E'_2$ by spontaneous emission and de-excited to ground level by collisions. Thus, they are again ready to go through the cycle.

## APPLICATIONS OF LASER:

- Medical applications:
  - Lasers are used in eye surgery by opthal mologists, especially in detached retina. The retina can be attached to the choroid by heating it over a no. of spots. The heating can be achieved by focussing a laser beam of predetermined intensity on the retina. This can be done by using Argon ion lasers
  - Laser angioplasty: lasers are used for treatment such as plastic surgery, skin injuries etc., this can be done by using Nd:YAG lasers.
  - Dermatologists use lasers for the treatment to remove moles and tumours developed in skin tissue and also to remove tattoos.
  - Lasers are used in stomatology- the study of mouth and its diseases. Mouth ulcers can be cured by exposing it to a laser beam.
  - Lasers are used to destroy kidney stones and gall stones. The laser pulses break the stones into small pieces.
  - Lasers are used in cancer diagnosis and therapy.
  - Lasers are used in blood loss less surgery

- Lasers are used to control haemorrhage
- Using organ and $CO_2$ lasers, liver and lung treatment can be carried out.
- Lasers are used in endoscopes to detect hidden parts.

- In scientific research:
  - Lasers are used to study the nature of chemical bonds.
  - Used for isotope separation.
  - Used to estimate the size and shape of biological cells.
  - Used to find the size of dust particles.
  - Used for recording and reconstruction of holograms.
  - Lasers are used to develop hidden finger prints and to clean delicate pieces of art.

# FIBRE OPTICS

## INTRODUCTION:

The improvement in the communication process would mean motivation to improve the transmission fidelity and at the same time to improve the data rate of transmission.

With the development of lasers, reliable and powerful coherent radiation became available. So, it was natural to use this light for communication process. There are two reasons for this

- Higher frequency
- More information carrying capacity compared to conventional radio and microwave carriers.

Light waves cannot travel far in open atmosphere as the energy gets very rapidly dissipated. Hence, some kind of guiding channel is needed just like for guiding electric current in a metal wire. Optical fibre provide necessary wave guide for light.

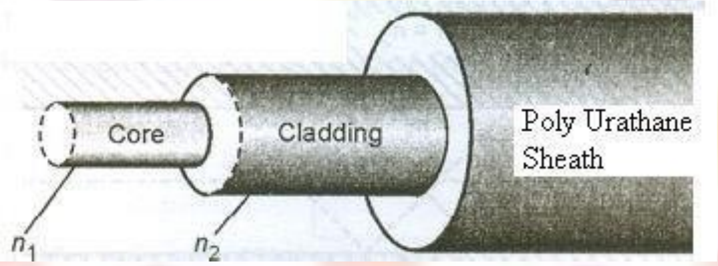
Fibre optics technology is increasingly replacing wire transmission lines in communication systems and is expected to be as electrical wiring even in our vehicles and houses very shortly.

## PRINCIPLE OF OPTICAL FIBER:

The optical fibres are based on the principle of total internal reflection. An optical fibre is a hair thin cylindrical fibre of glass. It is a flexible medium having a cylindrical shape consisting of three sections.

1. The core
2. The cladding and
3. The outer jacket.

The structure of optical fibre is

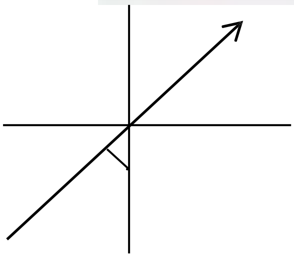


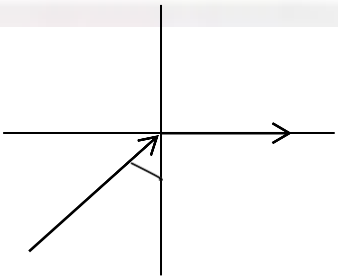
The fibre has a core surrounded with a cladding with refractive index slightly less than that of the core to satisfy the condition for total internal reflection. To give protection to the fibre, a outer jacket is used.

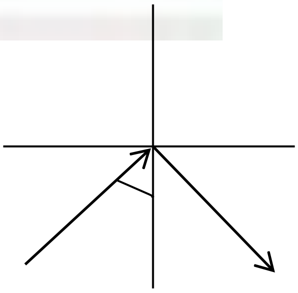
The light launched inside the core through its one end propagates to the outer end due to total internal reflection at the core cladding interface. This is the principle of optical fibre.

The condition for total internal reflection is

- $\mu_{CORE} > \mu_{CLADDING.}$
- $ANGLE\ IF\ INCIDENCE\ > CRITICAL\ ANGLE$







## ACCEPTANCE ANGLE AND ACCEPTANCE CONE:-

When we launch a light beam into a fibre at its one end, the rays which make the angle of incidence greater than the critical angle at core cladding interface undergo total internal reflection and propagate through the core. Other rays are lost.

So, we have to launch the beam at its end to enable the entire light to pass through the core. This maximum angle of launch is called acceptance angle.

Consider a cylindrical fibre wire which consists of an inner core of refractive index $n_1$and cladding of refractive index $\mu_2$ where $n_1 > n_2$.

Let $n_0$ be the refractive index of medium from which the light ray enters the fibre. This end is called launching end.

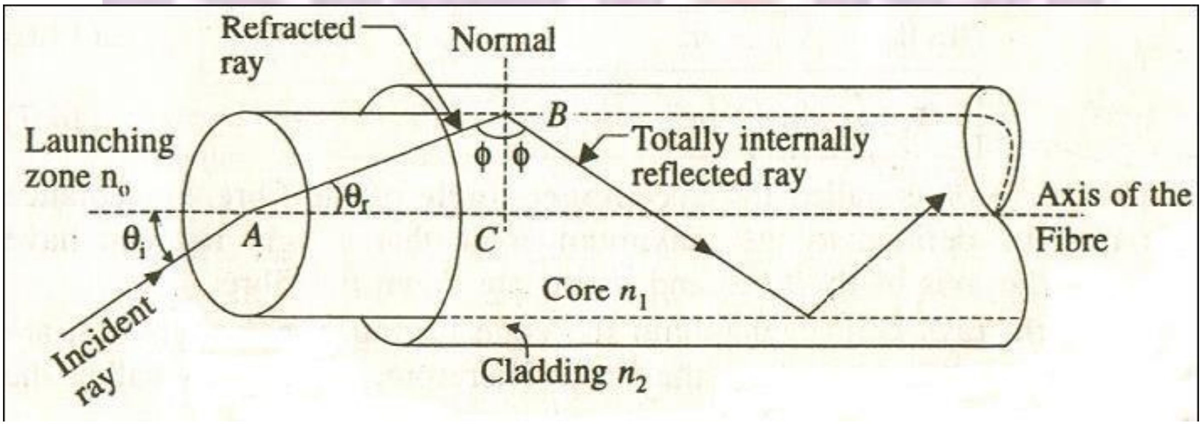
Let the light ray enter the fibre at an angle $\theta_i$ (acceptance angle) for which$\theta \geq \theta_c$, so that light stay within the fibre.

Applying snells law of refraction at point of ray OA in to the core, we have

$$\frac{\sin\theta_i}{\sin\theta_r} = \frac{n_1}{n_0} \quad \text{……………………} (1)$$

From triangle BCA,

$\theta_r = 90 - \theta$………………….. (2).



Therefore,

$$\sin\theta_r = \sin(90-\emptyset) = \cos\emptyset \text{ ............ } (3)$$

From (1) & (3)

$$\sin\theta_i = \frac{n_1}{n_0}\cos\emptyset \text{ ............. } (4)$$

Let $(\theta_i)_{max}$ occurs when $\emptyset = \theta_c$

$$\sin(\theta_i)_{max} = \frac{n_1}{n_0}\cos\theta_c \text{ ... ... ... ... } (5)$$

We know that

$$\sin\theta_c = \frac{n_2}{n_1} \text{ ... ... ... .... } (6)$$

Therefore,

$$\cos\theta_c = \sqrt{1-(\sin\theta_c)^2}$$

$$= \sqrt{1-\left(\frac{n_2}{n_1}\right)^2}$$

$$\cos\theta_c = \sqrt{\frac{n_1^2-n_2^2}{n_1^2}} \text{ ..................... } (7)$$

From (5) & (7)

$$\sin(\theta_i)_{max} = \frac{n_1}{n_0}\sqrt{\frac{n_1^2-n_2^2}{n_1^2}}$$

$$\sin(\theta_i)_{max} = \frac{\sqrt{n_1^2-n_2^2}}{n_0} \text{ ... ... ... } (8)$$

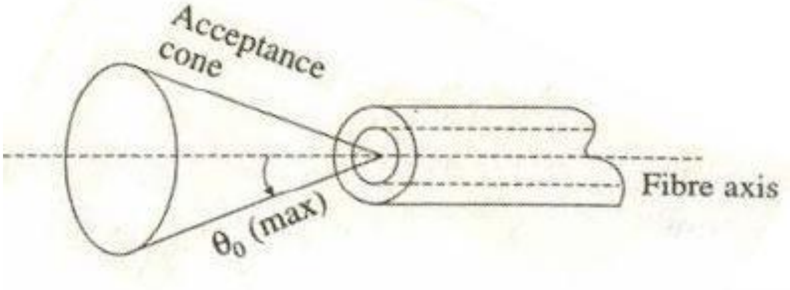
If launching medium is air, then $n_0 = 1$, $(\theta_i)_{max} = \theta_0$. Then,

$$\sin\theta_0 = \sqrt{n_1^2-n_2^2}$$

Here $\theta_0$ is called acceptance angle.

$$\theta_0 = \sin^{-1}\sqrt{n_1^2-n_2^2}$$

If the ray OA is rotated around the fibre axis keeping $\theta_0$ same, then it describes a conical surface. Now, only those rays which are funnelled into the fibre within this cone having a half angle $\theta_0$ are propagated. Therefore, the cone is called as acceptance cone.



## NUMERICAL APERTURE:-

Light gathering ability of a fibre is determined by using numerical aperture. This is defined as the sine of acceptance angle.

NA=$\sin\theta_0 = \sin\left(\sin^{-1}\frac{\sqrt{n_1^2-n_2^2}}{n_0}\right)$

$$NA = \frac{\sqrt{n_1^2 - n_2^2}}{n_0}$$

Consider,$\Delta = \frac{n_1^2-n_2^2}{2n_1^2} \rightarrow n_1^2 - n_2^2 = 2n_1^2\Delta$

$$NA = \frac{n_1\sqrt{2\Delta}}{n_0}$$

For launch medium, $n_0 = 1$

$$NA = n_1\sqrt{2\Delta}$$

Therefore, light collecting capacity is effectively dependent on refractive indices core and cladding and not on fibre dimensions.

## TYPES OF OPTICAL FIBERS:-

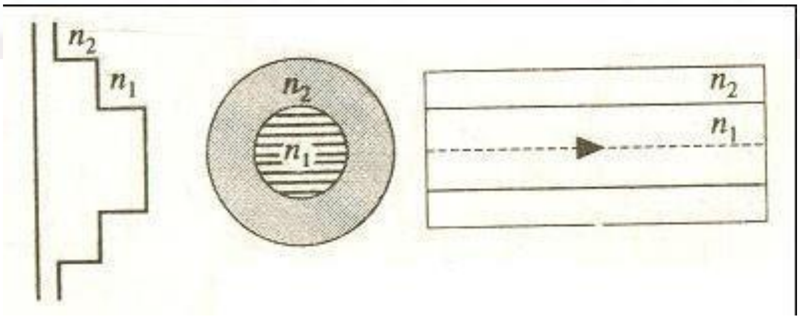
1. Step index fibre
2. Graded index fibre.

### Step index fibre:

These are the fibers in which the refractive index of core is maximum and constant throughout the core as

$$n(r) = n_1 \text{ for } r < a \text{ [core]}$$

$$n(r) = n_2 \text{ for } r > a \text{ [cladding]}$$



There is a step-wise decrease of refractive index from the core ($\square_1$) to the cladding ($\square_2$) at r=a. the refractive index of cladding material ($\square_2$) is given as

$$\square_2 = \square_1(1 - \Delta)$$

Where $\square_1$ → refractive index of core

Δ→fractional difference.

There are two types of step index fibres

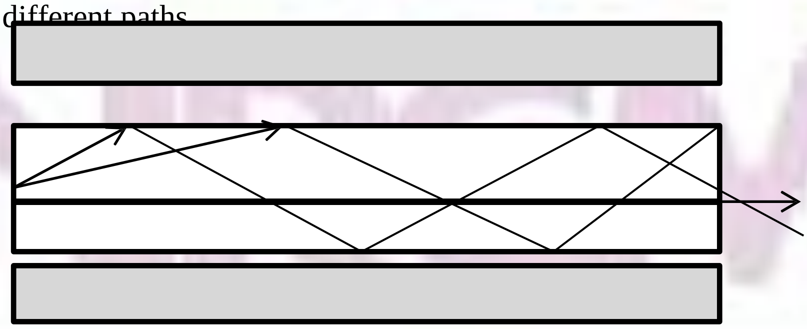
- Step index single mode fibre
- Step index multi-mode fibre.

In step index multimode fibre, the difference between μ of cladding and core is more. Further its core diameter is large. Generally, these are used in short distant communication because of its attenuation.

In step index single mode fibre, the difference between μ of core and cladding is very small and its core diameter is also very small. It has low attenuation and very high band width. It has low numerical aperture. These are used in long distant communication.

**Transmission of signal:-**

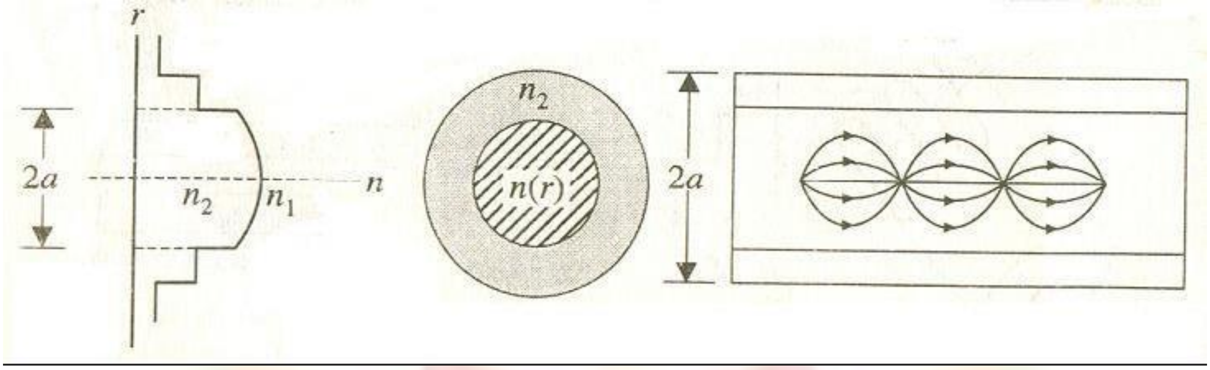
Generally the signal sent through the fibre is in digital form. Let us consider the propagation of one such pulse through the multimode step index fibre. The same pulsed signal travels in different paths.



Hence, three rays reach the received end at different times. The signal received at the end gets broadened. This is called intermodal dispersion. Due to this, the transmission rate and capacity is reduced. This difficulty is overcome in graded index fibres.

## Graded index fibre:-

A graded index fibre is a multimode fibre with a care consisting of concentric layers of different refractive indices. That is the refractive index of the core decreases with distance from the fibre axis. It has a maximum value at centre and decreases with ‘r’.



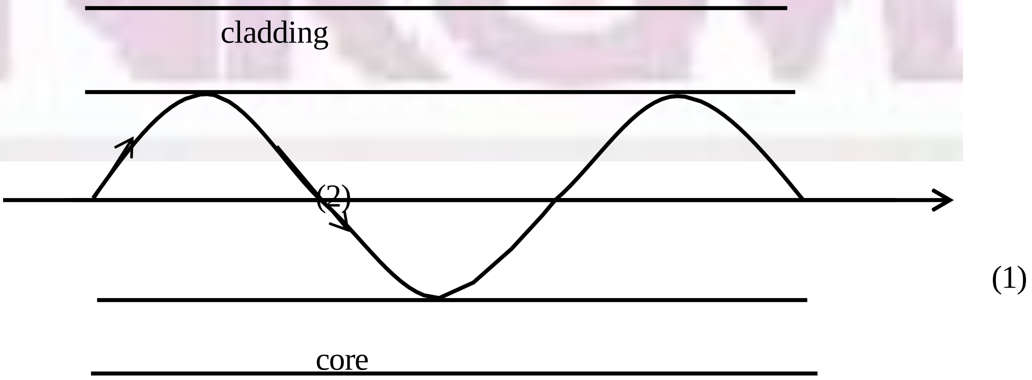
These fibres have several modes of transmission through the core. Because of the continuously varying refractive index across the core, the light rays are bent smoothly and converge repeatedly at points along the cable.

The light ray near the edge of the core take a longer path but travel faster since μ is lower. The variation of refractive index of core is

$$n(r) = n_1 \left[1 - \Delta \left(\frac{r}{a}\right)^{\infty}\right] \text{for r<a}$$
$$= n_1[1 - \Delta] \quad \text{for r} \geq \text{a}$$

## Transmission of signal :-

Let us consider a signal pulse travelling through graded index fibre in two differentpaths represented by (1) & (2)



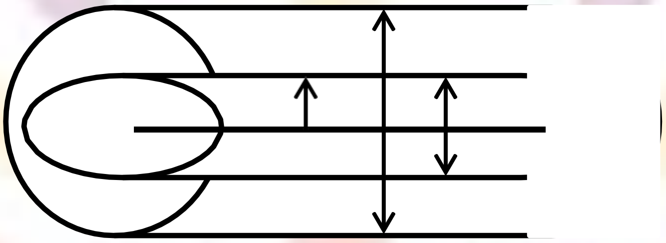
(1) Travels through higher refractive index

(2) Travels through lower refractive index.

Hence, both pulses reach the other end simultaneously. Then, the problem of intermodal dispersion can be reduced to minimum in using graded index fibre.

**Single Mode and Multi-Mode Fibre:-**

Consider a fibre with core diameter of 2a, and cladding diameter of 2b represented in figures.



Let r be a distance of core position from the axis when a light is launched at one end, the light progresses through the fibre core in different trajectories. Each trajectory is called as a mode.The no. of modes that a fibre allows through it depends upon the diameter of core. If the core diameter is small it allows only one mode to travel through it. Then, the fibre is called single mode or monomode fibre.

In single mode fibre only $\square\square_{11}$ mode is allowed to travel through it. $\square\square_{11}$[the ray along fibre axis]. The monomode fibres has very small core diameter less than 10µm. if fibre allows more no. of modes then it is called multimode fibre. The core diameter of a multimode fibre is of the order of 50µm.

**V-number of a fibre:-**

This indicates the no. of possible propagation modes in the core.

$$\square = \frac{2\square}{\square}\square(\square\square)$$

Where, $\square$ is the wavelength of the propagating waves.

α is the radius of the core

NA is the numerical aperture.

- The no. of modes propagating through the step-index fibre.

$$N_{SI} = \frac{V^2}{2}$$

- For the SI two possible polarizations are there.

$$N_{SI} = 2\left(\frac{V^2}{2}\right) = V^2$$

Therefore no. of modes in SI fibre=$\square^2$

- The no. of modes propagating in graded index fibre

$$N_{GI} = \left[\frac{\alpha}{\alpha + 2}\right]\left[\frac{V^2}{2}\right]$$

For parabolic profile,

$$\alpha = 2$$

$$N_{GI} = \frac{V^2}{4}$$

For GI two possible polarizations are there.

$$N_{GI} = 2\left(\frac{V^2}{4}\right)$$

$$N_{GI} = \frac{V^2}{2}$$

$N_{GI} = \frac{N_{SI}}{2}$.

## ATTENUATION IN OPTICAL FIBERS:-

The main specification of a fibre optic cable is its attenuation. The power of the light at the o/p end is found to be always less than the power launched at the i/p end. The attenuation is found to be a function of fibre material, wavelength of light and length of the fibre.

Losses intrinsic to fibres result in attenuation. These losses are

- Scattering losses
- Absorption losses
- Bending losses

**Scattering losses:**

By its nature, glass is a disordered structure in which there are macroscopic variations around the average density and local microscopic variation in composition.

Each of these give rise to fluctuations of refractive index on a scale. Due to this light is scattered in the manner known as Rayleigh ‘s scattering. This scattering light is then lost from the fibre.

The loss caused by this mechanism can be minimised by selecting proper fibre fabrication method. The loss is higher in multicomponent glasses because of compositional variations.

Rayleigh scattering loss coefficient $\alpha_R = \frac{A}{\lambda^4}$, A-constant for given material.

**Absorption losses:-**

Three different mechanisms contribute to absorption losses in glass fibres. There are

- UV absorption
- IR absorption
- Ion resonance absorption

In pure fused silica, absorption of UV radiation around 0.14 µm results in ionisation. Thus, there is a loss.

Absorption of IR photons by atoms with in glass molecules results in increase of random mechanical vibrations.

$OH^-$ions are present in the material due to trapping of minute quantities of water molecules during manufacturing.

**Bending losses:-**

The distortion of the fibre from the ideal straight line configuration may also result in losses in fibre. Tight bends cause some of the light not to be internally reflected but to propagate in to the cladding and be lost. The loss coefficient is

$$\alpha_B = C \exp\left(-\frac{R}{R_c}\right)$$

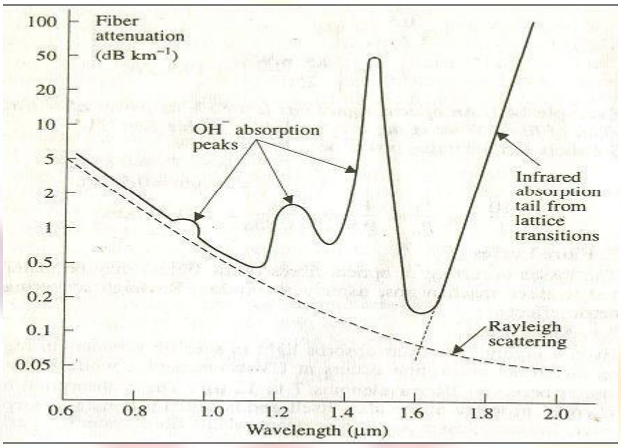
Where c - constant

R - bend radius

$R_c = \frac{a}{(NA)^2}$

a- radius of the fibre

NA - numerical aperture.



**Loss in decibels:**

Attenuation is generally measured in terms of the decibels (dB) which is a logarithmic unit. The decibel loss of optical power in a fibre is

Loss in optical power $= -10 \log \left(\frac{P_{out}}{P_{in}}\right)\ dB.$

Attenuation loss is given by the number of decibles per kilometre of fibre.

$$\frac{\text{Loss}}{Km} = -\frac{10}{L} \log \left(\frac{P_{out}}{P_{in}}\right)\ dB/Km.$$

## APPLICATIONS OF OPTICAL FIBERS:-

OFC are mainly used in three different fields.

1. Fiber optic communication: The various applications of fibre optics in telecommunication area include the voice telephones, video phones, telegraph services, various new services and data networks all transmitted over common carrier links.
2. Medical application: Endoscopic applications
3. Sensor field:Various kinds of sensors have been developed. They are temperature sensors, pressure sensor, acoustic sensor, current sensor, flow meter, strain detector, chemical sensor, humidity sensor etc.

## Optical sensors:

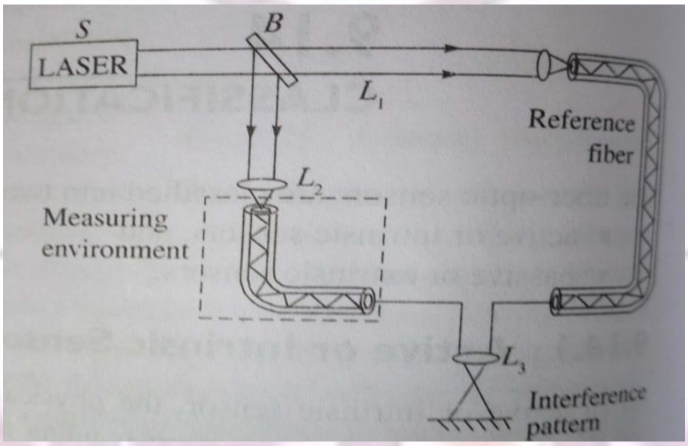
The fiber optic sensors are classified in to two types

1. Active sensors
2. Passive sensors

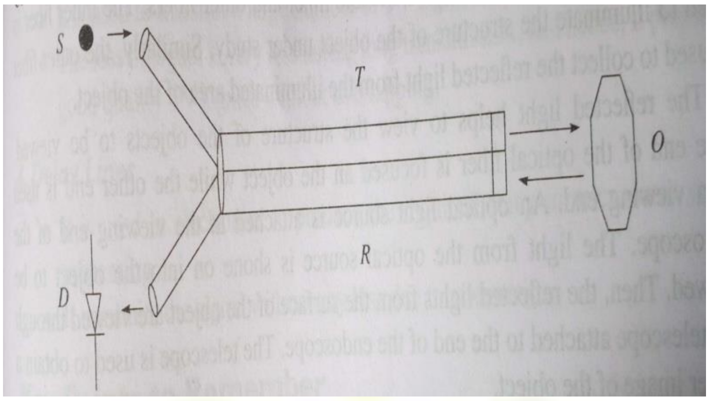
**Active sensors**: the physical parameters to be sensed act directly on the fiber. These are otherwise called as intrinsic sensors.

**Passive sensors**: in passive sensors, separate sensing elements are used and optical fibers are used as guiding media

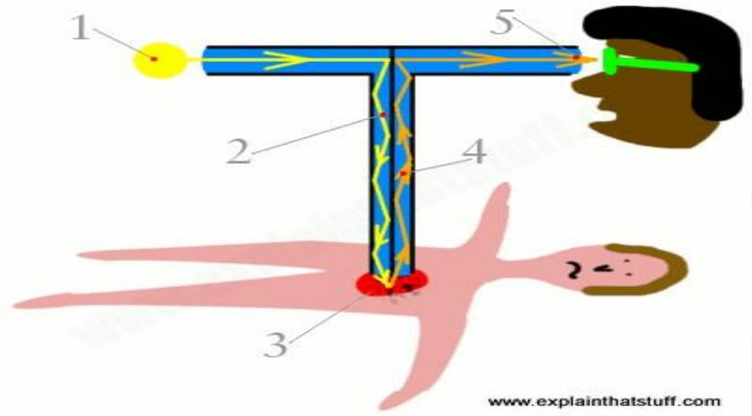
**Pressure sensor:**The pressure sensor is a best example for active sensor.The principle behind the pressure sensor is interference, I,e., the path difference between the reference beam and the beam passing through the environment.High energy laser light from the source is made to fall on a beam splitter placed at a angle 45. The beam splitter splits incident light into two components.One passes through reference end and another through environment end.Finally the path difference between the o/p beams sense the change in pressure.



**Displacement sensor**: The displacement sensor is a best example for passive sensor. The light from the source is made to fall on the object after passing through the transmitting fiber. The light reflected from the moving object is received by the receiving fiber and the same is detected by the detector. The change in the intensity of light measures the movement of the object. Increase intensity of light resembles that object is moving towards the sensor while decrease in intensity of light resembles that object is moving away from the sensor.



**Endoscopic applications:**One of the two main endoscope cables carries light from a bright lamp in the operating room into the body, illuminating the cavity where the endoscope has been inserted.The light bounces along the walls of the cable into the patient's body cavity. The diseased or injured part of the patient's body is illuminated by the light shining in. Light reflected off the body part travels back up a separate fiber-optic cable, bouncing off the glass walls as it goes.The light shines into the physician's eyepiece so he or she can see what's happening inside the patient's body. Sometimes the fiber-optic cable is directed into a video camera.



# UNIT-5

# DIELECTRIC PROPERTIES

## INTRODUCTION:

Dielectrics are the substances which do not contain free electrons or the number of such electrons is too low to constitute the electric current. So, the dielectric is insulating materials. Dielectrics are non metallic materials of high specific resistance and have negative temperature coefficient of resistance.

Comparable to conductors, the dielectrics are

1. Insulators
2. Doesn’t conduct electricity
3. Charge given to them remains localized
4. For particular field strength, they lose their insulating character.

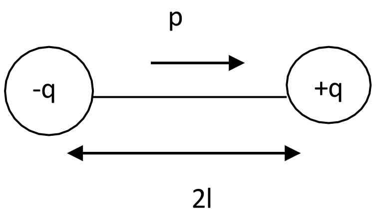
The molecules in which the centre of gravity due to positive and negative charges coincides are called non polar molecules otherwise polar molecules. For non polar molecules ($H_2$, $N_2$, $O_2$, $CO_2$, BENZENE), the dipole moment is zero and they have symmetrical structure. For polar molecules (H2O, HCl, CO, N2O, NH3), the dipole moment is permanent and they have unsymmetrical structure.

When non polar dielectrics are placed in a electric field, they get polarized. This means that the induced surface charges appear which tend to weaken the original field within the dielectric.

When polar molecules are placed in an electric field their dipole moment increases with increase in electric field or decrease in temperature.

## ELECTRIC DIPOLE:

The arrangement of two equal and opposite point charges at a fixed distance is called an electric dipole.



## DIPOLE MOMENT:

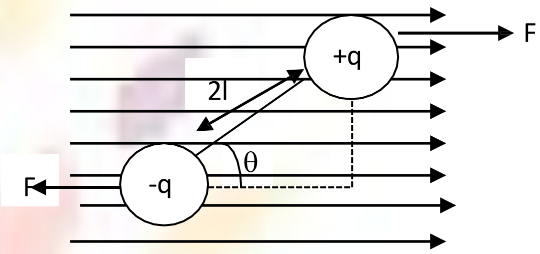
The product of the magnitude of either charge and the distance between the charges is called as electric dipole moment.

$$\square = \square \times 2\square = 2\square\square$$

It is a vector quantity and units are “coulomb- meter.

When the dipole is placed in a uniform electric field the couple acting on it is

$$\tau = pE\ \sin\theta$$



$$\sin\theta = \frac{x}{2l}$$

$$x = 2l\ \sin\theta$$

$$\tau = F \times x = qEx$$

$$\tau = qE(2l\ \sin\theta) = pE\ \sin\theta$$

If θ=90 and E=1N/c then τ=p. Thus, dipole moment may be defined as the moment of the couple acting on the dipole place perpendicular to the direction of uniform electric field of unit intensity.

## DIELECTRIC CONSTANT:

It is defined as the ratio of capacitance of the condenser with dielectric to the capacitance of the same condenser without dielectric.

$$K = \frac{C}{C_o}$$

It is also defined as the ratio of permittivity of the medium to the permittivity of the free space.

$$K = \varepsilon_r = \frac{\varepsilon}{\varepsilon_o}$$

K has no units and K=1 for vacuum and k is infinity for metals.

## POLARIZABILITY:

When the strength of the electric field is increased, the induced dipole moment is also increased. So,

$$p \propto E$$

$$p = \alpha E$$

Where αis called polarisability.

So, polarisability is defined as induced dipole moment per unit electric field. Electric dipole moment per unit volume is called dielectric polarization.

$$\vec{P} = \frac{q'(2l)}{A(2l)} = \frac{q'}{A}$$

Where P is called polarization vector.

## ELECTRIC SUSCEPTIBILITY:

When a dielectric is placed in electric field, it is polarized. So,

$$\vec{P} \propto \vec{E}$$

$$\vec{P} = \chi \vec{E}$$

Where χ is called electric susceptibility. So, it is defined as the ratio of polarization vector to the electric field intensity in the dielectric.

## DISPLACEMENT VECTOR:

when a dielectric is placed in between the plates of a condenser then

$$E = E_o - E'$$

$$\frac{q}{\varepsilon_o K A} = \frac{q}{\varepsilon_o A} - \frac{q'}{\varepsilon_o A}$$

$$\frac{q'}{\varepsilon_o A} + \frac{q}{\varepsilon_o K A} = \frac{q}{\varepsilon_o A}$$

$$\frac{q'}{A} + \frac{q}{\varepsilon_o K A}\varepsilon_o = \frac{q}{A}$$

$$\vec{P} + \varepsilon_o E = \frac{q}{A}$$

$$\vec{P} + \varepsilon_o E = \vec{D}$$

Where D is called displacement vector.

Note: since D=q/A & E=q/ ($\varepsilon_o$KA). Then D=$\varepsilon_o$KE

$$\vec{D} = \vec{P} + \varepsilon_o E$$

$$\varepsilon_o \mathrm{KE} = \varepsilon_o \mathrm{E} + \mathrm{P}$$

$$\varepsilon_o \mathrm{E}(\mathrm{K}-1) = \mathrm{P} = \chi \vec{E}$$

$$\varepsilon_o \mathrm{E}(\mathrm{K}-1) = \chi \vec{E}$$

$$\varepsilon_o(\mathrm{K}-1) = \chi$$

## TYPES OF POLARIZATION:

There are three mechanisms by which electric polarization can occur in dielectric materials when they are subjected to an external electric field. They are

1. Electronic polarization
2. Ionic polarization
3. Orientation polarization.

**Electronic polarization:**

On the application of electric field, the displacement of positively charged nucleus and negatively charged electrons of the atom in opposite directions, results in electronic polarization.

Since the nucleus and centre of electron cloud are separated, dipole moment is created in each atom. So, induced dipole moment ($p_e$) and dielectric polarization is proportional to field strength (E).

$$P_e \propto E$$

If there are N no. of atoms then,

$$P_e \propto NE$$

$$P_e = \alpha_e NE \ldots\ldots\ldots\ldots\ldots (1)$$

Where $\alpha_e = 4\pi\varepsilon_o R^3$ is called electronic polarisability.

**Ionic polarization:**

This type of polarization occurs only in those dielectric materials which posses ionic bonds such as NaCl. When such material is subjected to an external electric field, the adjacent ions of opposite signs undergo displacement. Therefore, ionic polarization is due to displacement of cations and anions in opposite direction.

$$P_i = \alpha_i E$$

Where $_i = \frac{e^2}{\omega_o{}^2}\left(\frac{1}{m} + \frac{1}{M}\right)$ *is called ionic polarisability.*

**Orientation polarizasbility**:

Polar dielectrics exhibit orientation or dipolar polarizability.

When an external field is applied to polar dielectrics, they tend to align themselves in the direction of external applied field. The polarization due to such alignment is called orientation polarization. This is dependent on temperature and decreases with increase in temperature.

With increase of temperature, the thermal energy tends to randomize the alignment. So,

$$P_o = N\alpha_o E$$

Where $\alpha_o = \frac{\mu^2}{3KT}$ is called orientation polarizability.

## Total Electric polarization:

The Total Electric polarization is the sum of electronic polarization, ionic polarization, orientation polarization, and space charge polarization. Among these, the space charge polarization is very small compared to others. So it can be neglected. Therefore the total polarizability is given by

$\alpha = \alpha_e + \alpha_i + \alpha_0$

Therefore,

$$P = N\left(4\pi\varepsilon_o r^3 + \left(\frac{e^2}{\omega_0{}^2}\left(\frac{1}{m}+\frac{1}{M}\right)\right) + \frac{\mu^2}{3KT}\right)E$$

This equation is called Langevin- Debye equation

## INTERNAL FIELDS IN SOLIDS:

In solids, the atoms are very close to each other and interact considerably. When an electric field is applied, the atoms are polarized. Each of the atoms develops a dipole moment. i.e., each atom acts as dipole. Therefore, electric field at any given atom is the sum of applied electric field plus the electric field due to surrounding dipoles. This resultant local field is called as internal field.

### Expression:

Consider a solid dielectric be placed between the plates of a parallel plate capacitor and let there be an imaginary spherical cavity around the atom a inside the dielectric. It is also assumed that the radius of the cavity is large compared to the radius of the atom. The internal field at the atom site A is given by

I. $E_1$ field:

$E_1$ is the field intensity at A due to the charge density on the plates.

$$E_1 = \frac{D}{\varepsilon_o}$$
$$D = P + \varepsilon_o E$$

Therefore,

$$E_1 = \frac{P + \varepsilon_o E}{\varepsilon_o}$$
$$E_1 = \frac{P}{\varepsilon_o} + E$$

II. $E_2$ field:

$E_2$ is the field intensity at a due to the charge density induced on the two sides of the dielectric.

$$E_2 = -\frac{P}{\varepsilon_o}$$

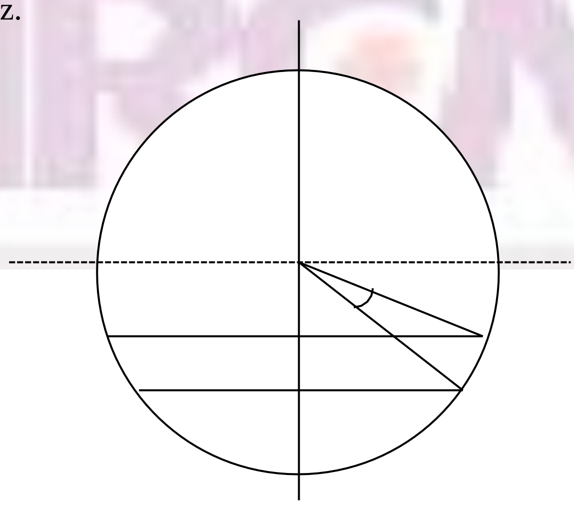
$$E_1 = \frac{P}{\varepsilon_o} + E$$

III. $E_3$ field:

It is the field due to other atoms contained in the cavity. Since it is a cubic structure, due to symmetry $E_3$=0.

IV. $E_4$ field:

It is the field due to polarization charges on the surface of the cavity and was calculated by Lorentz.



If dA is the surface area of the sphere of radius r lying between θ and θ+dθ. then,

dA=2Π(PQ)(QR)

PQ=r sin θ

QR=r dθ

Therefore, $dA=2\Pi r^2 \sin\theta\, d\theta$

The charge on the surface dA is

dq=P cos θ dA

$=P2\Pi r^2 \sin\theta \cos\theta\, d\theta$

$=P\Pi r^2 \sin 2\theta\ \ d\theta$

Therefore,

$$dE_4 = \frac{dq \times 1 \times \cos\theta}{4\pi\varepsilon_o r^2}$$
$$= \frac{P}{4\varepsilon_o} \cos\theta \sin 2\theta\ \ d\theta$$

So,

$$E_4 = \int d\,E_4$$
$$= \frac{P}{4\varepsilon_o} \int \cos\theta \sin 2\theta\ \ d\theta$$
$$= \frac{P}{2\varepsilon_o} \int \cos^2\theta \sin\theta\ d\theta$$
$$= \frac{P}{2\varepsilon_o} \int \cos^2\theta\ \ d(-\cos\theta)$$
$$= -\frac{P}{6\varepsilon_o} [-1-1]$$
$$= \frac{P}{3\varepsilon_o}$$

THEREFORE INTERNAL FIELD,

$$E_i = E + \frac{P}{\varepsilon_o} - \frac{P}{\varepsilon_o} + 0 + \frac{P}{3\varepsilon_o}$$
$$E_i = E + \frac{P}{3\varepsilon_o}$$

## CLASSIUS-MOSOTTI RELATION:

Consider a dielectric having cubic structure. Since for these materials, there are no ions and permanent dipoles, $\alpha_i=\alpha_o=0$

Hence,

$$P = \alpha_e N E_i = \alpha_e N\,[E + \frac{P}{3\varepsilon_o}]$$

$$P\,[1 - \frac{\alpha_e N}{3\varepsilon_o}] = [\alpha_e NE]$$

$$P = \frac{[\alpha_e NE]}{[1 - \frac{\alpha_e N}{3s_o}]}$$

we know that

$$\varepsilon_o E(K - 1) = P$$

So,

$$\varepsilon_o E(\varepsilon_r - 1) = \frac{[\alpha_e NE]}{[1 - \frac{\alpha_e N}{3s_o}]}$$

$$1 - \frac{\alpha_e N}{3\varepsilon_o} = \frac{[\alpha_e N]}{[\varepsilon_o\,(\varepsilon_r - 1)]}$$

$$1 = \frac{\alpha_e N}{3\varepsilon_o}\,[1 - \frac{3}{[(\varepsilon_r - 1)]}]$$

$$\frac{\alpha_e N}{3\varepsilon_o} = \frac{1}{1 + \frac{3}{[(s_r - 1)]}} = \frac{\varepsilon_r - 1}{\varepsilon_r + 2}$$

This is called classius-mosotti relation.

**Piezo electricity:**

Piezo electric phenomenon was discovered by curie brothers in 1880. Some of the materials when compressed or stretched in a certain direction become polarized and polarization charges appear on its surface.

Polarization of a dielectric as a result of mechanical deformation is called as piezo electric effect. The crystals that exhibit this effect are called piezo electrics.

These materials exhibit inverse piezo electric effect. When electric stress is applied to materials they become strained. Strain is proportional to applied field. This piezoelectric effect is utilized in conversion of mechanical energy in to electrical energy and vice versa.

Example: quartz crystal, ceramic.

Applications:

1. Quartz is used for filter, resonator.
2. Rochelle salt used as transducer in gramophones, ear phones.
3. Ceramics are used as high voltage generators, accelerometers.
4. Semiconductors used as amplifier of ultrasonic waves.

## PYRO ELECTRICITY:

Pyro electric effect is the change in the spontaneous polarization when the temperature of the specimen is changed.

The pyro electric coefficient λ is defined as the change in polarization per unit temperature change of specimen.

$$\lambda = \frac{dP}{dT}$$

Applications: the pyro electric materials such as $BaTiO_3$, $LiNiBO_3$ etc are used to make very good infra red detectors which can operate at room temperature.

## FERRO ELECTRICITY:

There are some classes of dielectrics which posses a

i. Non linear relation between P & E.
ii. Dielectric constant that changes with temperature.
iii. Electrical hysteresis.
i.e., variation of polarization with applied field.

Therefore, Ferro electric materials are that class of dielectric materials which popsses electrical properties which are analogues to the magnetic properties of a ferro magnetic materials.

Example: $BaTiO_3$, $KH_2PO_4$, $NaKC_4H_4O_6.4H_20$, Rochelle salt.

Applications:

1. Used to manufacture small sized capacitors of large capacitance
2. Used as memory devices in computers
3. Used to detect infrared solutions
4. Used in electromechanical filters.

# MAGNETIC PROPERTIES

## INTRODUCTION:

Magnetic materials are those substances which get magnetized when placed in a magnetic field. So, the substance develop magnetization which may be parallel or antiparallel to the applied field. Depending upon the magnitude and sign of response to the applid field, and also on the basis of temperature on the magnetic properties, all materials are classified as follows.

1. Diamagnetic materials
2. paramagnetic materials
3. ferromagnetic materials
4. antiferromagnetic materials
5. ferrimagnetic materials

## PERMEABILITY:

The magnetic permeability (μ) of any material is the ratio of magnetic induction in the sample to the applied magnetic field intensity.

$$\mu = \frac{B}{H}$$

Units are H/m.

## FIELD INTENSITY:

The magnetic field intensity (H) at any point in the magnetic field is the force experienced by an unit north pole placed at that point.

Units are A/m

## MAGNETIC FIELD INDUCTION:

The magnetic field induction (B) or magnetic flux density in any material is the no.of lines of magnetic force passing through unit area perpendicularly.

Units are Wb/m$^2$ or Tesla

The magnetic induction B and intensity H are related by

$B = \mu_0 H$

Where $\mu_0$ is permeability of free space=$4\pi\times10^{-7}$ H/m

In the medium, $B = \mu H$.

The ratio of $\mu/\mu0$ is called relative permeability.so, $\mu_{\square} = \frac{\mu}{\mu_0}$.

## MAGNETIZATION:

When a magnetic substance is placed in a magnetic field, the substance acquires magnetic moment (M). The magnetic moment per unit volume of the substance is called as intensity of magnetization (I).

$$\square = \frac{\square}{\square}$$

Units are A/m

## MAGNETIC SUSCEPTIBILITY:

It is defined as the ratio of intensity of magnetization I to magnetic intensity H. Therefore,

$$\chi = \frac{\square}{\square}$$

It has no units.

## CLASSIFICATION OF MAGNETIC MATERIALS:

The distinction of magnetic materials depends upon whether the atoms carry permanent magnetic dipoles or not.

Materials which are lack of permanent dipoles are called diamagnetic.

If the atoms of the material carry permanent magnetic dipoles, such materials may be

Paramagnetic- permanent dipoles do not interact among themselves.

Ferromagnetic- if they interact and line up themselves in parallel.

Anti Ferro & ferri magnetic: if they interact and line up themselves anti parallel

In anti ferromagnetic materials, the magnitude of permanent dipoles aligned anti parallel are equal and hence magnetization vanishes.

In ferri magnetic materials, the magnitude of permanent dipoles aligned anti parallel are not equal and hence exhibiting magnetization

**Diamagnetic:**

The substance which when placed in the magnetic field acquire feeble magnetism opposite to the direction of the field are known as dia magnetic substances.

Eg: bismuth (Bi), zinc (Zn), copper (Cu), silver (Ag), gold (Au)

Properties:

1. when a bar of dia-magnetic material is suspended freely between two magnetic poles, then the axis of the bar becomes perpendicular to magnetic field.
2. $\mu<1$ and $\chi$ is negative.
3. When U-tube containing diamagnetic liquid is placed in magnetic field then it shows depression.
4. When a dia magnetic substance is placed in non uniform magnetic field then it tends to move from stronger part to the weaker part of the field.

**Paramagnetic:**

The substance which when placed in a magnetic field, acquire feeble magnetism in the direction of magnetic field are known as paramagnetic substance.

Eg: aluminum (Al), platinum (Pt), manganese (Mn), oxygen ($O_2$).

Properties:

1. When a bar of paramagnetic substance is placed in a magnetic field, it tries to concentrate the lines of force in to it.
2. $\mu>1$ and $\chi$ is small & positive.
3. When a bar of paramagnetic substance is suspended freely between two magnetic poles, its axis becomes parallel to magnetic field.
4. When U-tube containing paramagnetic liquid is placed in magnetic field then it shows a rise.

5. When a dia magnetic substance is placed in non uniform magnetic field then it tends to move from weaker part to the stronger part of the field.

## Ferro magnetic substances:

The substance which when placed in a magnetic field, becomes strongly magnetized in the direction of field are known as Ferro magnetic substances.

Eg: iron (Fe), nickel (Ni), cobalt (Co), magnate ($Fe_3O_4$).

Properties:

1. When a Ferro magnetic material is subjected to the influence of a magnetic field, there will be a crowding of flux lines in the body.
2. They are attracted by magnets.
3. Obeys curies law

$$\square \propto \frac{1}{\square}$$

4. Above curies temperature, Ferro magnetic substance changes to paramagnetic substance.
5. These all materials posses the propertie3s of paramagnetic substances.

## DOMAIN THEORY OF FERROMAGNETISM ON THE BASIS OF HYSTERESIS CURVE:

In Ferro magnetic substances, the atoms due to certain mutual interaction, form innumerable small effective regions called **domains**. Each domain contains 1017 to 1021 atoms whose magnetic axes are aligned in the same direction even in the absence of any external field. Each domain is strong magnet.

When a ferromagnetic substance is placed in an external magnetic field, the magnetic moment increase in two different ways:

1. ***By the displacement of the boundaries of the domains:***

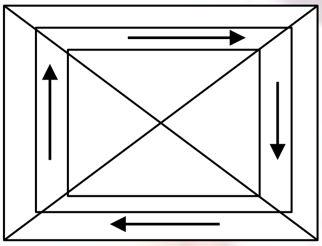
   When the substance is placed in magnetic field, the domains which are oriented favorable with respect to the external field increases in size while those oriented opposite to the external field are reduced.

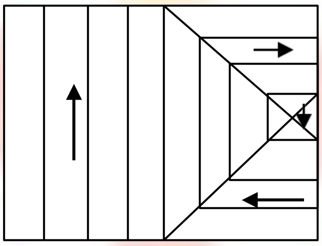
2. ***By the rotation of domains:***

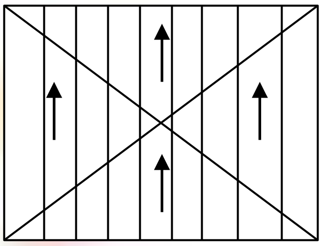
The domains rotate until their magnetic moment aligned more or less in the direction of external magnetic field.

When external field is weak, the substance is magnetized mostly by the boundary displacement. On the other hand, in strong magnetic fields, the magnetization takes place mostly by the rotation of domains.

On the removal of external field, the boundaries do not move completely back to their original position and hence the substance is not completely demagnetized. At high temperatures, the domains break up and ferromagnetic substance becomes paramagnetic.







## HYSTERESIS CURVE:

Consider an unmagnetised ferromagnetic substances in a magnetizing field. The substance shows a relation between intensity of magnetization and strength of magnetic field. Thios property is called hysteresis.

i. When a substances is slowly magnetized, the intensity of magnetization I increases with field H. As part OA.

   At point A, the intensity of magnetization I becomes constant. That is the state of magnetic saturation.

ii. Now, consider that magnetizing field H is decreased it is onvious from figure that intensity of magnetization also decreases but it doesn't follows the path AO. It follows the path AB. At B, I has some value even H=0. The value of intensity of magnetization for which H=o is called retentivity or residual magnetism.

iii. Further consider the direction of H is reversed. As H increases in reverse direction, I decreases and becomes zero. The value of magnetizing field for which residual magnetism is destroyed is called coercivity. Further increase of H in reverse direction gives saturation point D.

iv. If now the field is increased in steps, a curve DEFA is obtained. In throughout the cycle, I lags behind H. thus, lagging of intensity of magnetization behind the magnetic field is called hysteresis and path ABCDEFA is called hysteresis loop.

## SOFT AND HARD MAGNETIC MATERIALS:

| Hard magnetic materials | Soft magnetic materials |
|---|---|
| 1. These materials have large hysteresis loss due to large hysteresis loop area. | 1. These materials have less hysteresis loss due small hysteresis loop area. |
| 2. In these materials domain wall movement is difficult. | 2. In these domain walls movement is relatively easier. |
| 3. Coercivity and retentivity are large. Hence magnetization and demagnetization of these materials is difficult. | 3. Coercivity and retentivity are small. Hence magnetization and demagnetization of these materials is easy. |